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A Study of the Velocity of Sound in Air

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This study of the velocity of sound in air involves the use of the magnetostriction oscillator in an experiment similar to those of G. W. Pierce and others, who used piezoelectric crystals as sources of sound. The wave system generated by the source is investigated by observing the reactions of the source when the sound waves are reflected back upon it from a moveable reflector. The range of frequencies used extends from 20,000 to 70,000. The irregularities of the wave system near the source are studied in some detail. It is found that these irregularities vary with the frequency, as well as with the diameters of both the source and the reflector, and that they vanish at relatively large distances from the source. The values of the velocity of sound then obtained show no variations with respect to the frequency.

THIS investigation continues the studies of the velocity of sound in air which were begun by G. W. Pierce[1] and carried forward by Reid.[2] Professor Pierce and Dr. Reid used piezoelectric crystals driven by vacuum-tube oscillators as sources of sound in what is sometimes called an acoustical interferometer. The use of crystals restricted the range of their experiments to frequencies of forty thousand or greater; and their results raised some questions concerning the velocity of sound at frequencies in the vicinity of forty thousand.

The experiments to be described here are, in principle, like those of Professor Pierce, except that they involve the use of his magnetostriction oscillator[3] as the source of sound. The investigation was directed toward the measurement of the velocity of sound in relatively unconfined air at frequencies ranging from 20,000 to 70,000 and also toward the study of certain irregularities in the observed wave system near the source.

When sound waves encounter a reflector and are thereby sent back to the source, the reflected wave will either aid or hinder the vibration of the source, accordingly as the phase of the returning wave relative to that of the vibrating source is favorable or unfavorable. The presence of the reflector in a certain position will increase the acoustical impedance of the medium, as seen from the source. This hindrance to the vibration of the source entails a change in the plate current of the driving oscillator. As the reflector is moved through such a critical position, the needle of the ammeter in the plate circuit executes a small deflection, the sign of the deflection being determined by the polarization of the grid of the oscillating vacuum tube. As the reflector is moved toward or away from the source, it presently occupies another position

[1] G. W. Pierce, Proc. Am. Ac. **60**, 5 (1925).
[2] C. D. Reid, Phys. Rev. **35**, 814 (1930).
[3] G. W. Pierce, Proc. Am. Ac. **63**, 1 (1928).

at which a similar reaction occurs. In the absence of diffraction phenomena, the change in path introduced by this displacement of the reflector is one wave-length, the displacement itself being equal to one-half wave-length. By observing the positions of the reflector at which these reactions occur over a long range, the wave-length may be accurately determined. The frequency of the source is measured independently by electrical methods. The velocity of sound is then the product of the frequency into the wave-length and its value may be reduced to its equivalent value for any conditions of temperature and of relative humidity.

Apparatus and Procedure

The sound waves were generated by the vibrating end of the metal core of the magnetostriction oscillator. These cores were solid rods of annealed nichrome, 2.54 cm in diameter, and of various lengths from 3.43 cm to 12.38 cm. Since the reactions of magnetostrictive rods are much less intense than those of piezoelectric crystals under similar circumstances, it was necessary to give the rods the greatest possible freedom. To that end, the rods were so mounted as to lie freely balanced in a V-shaped opening cut into a slab of Bakelite. This mounting is much superior to any contrivance involving clamping. No longitudinal creeping of the rods was ever observed.

The forward one of the two inductance coils around the rod was wound in the form of a cone to permit the introduction of a conical, pasteboard shield around the source. The apex of the cone was cut away, so that the vibrating face of the rod projected through from within. This shield discouraged the formation of secondary standing wave systems and its use greatly improved the consistency of the observations. The mounting of the rod, coils and shield was made as compact as possible and was supported rigidly from the rear by a heavy metal bar projecting horizontally from a slender concrete pedestal.

The electrical circuit of the magnetostriction oscillator differed from Professor Pierce's usual form only in that the oscillating circuit was placed entirely at low potential to improve the electrical stability of the system. In order to amplify the changes in the plate current caused by the reactions, it was necessary to use a two-stage, direct-current amplifier. It was also convenient to insert one stage of alternating current amplification for the measurement of the frequency. The stability of the system demanded the use of reliably constant and non-inductive coupling resistances, careful elimination of slightly imperfect cells and the use of lead connectors to the filament batteries to avoid unsteady electromotive forces should the electrolyte creep up to the binding posts. The oscillator and amplifiers are shown schematically in Fig. 1.

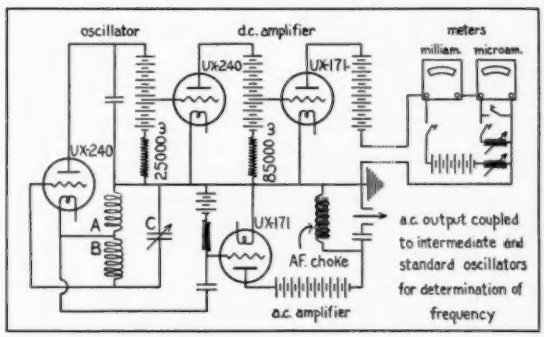

FIG. 1. Schematic diagram of the oscillator, the amplifiers and the observing meters. The magnetostrictive rod extends through the coils *A* and *B*.

The observing meter system (cf. Fig. 1) was inserted in the plate circuit of the second amplifier tube. It consisted of a milliammeter and a microammeter (180 microamp. scale) in series. The microammeter was shunted with a switch, in parallel with a variable resistance to control the sensitivity. An auxiliary battery, in series with another variable resistance, was shunted across both meters to deliver a counter current to reduce the steady plate current through the meters practically to zero. The shunting switch being then released, the microammeter registered the changes of the plate current caused by the reactions.

Observations were made with five different reflectors; their diameters ranging from $\frac{1}{2}$ to 4 inches. The $\frac{1}{2}$-inch reflector was made of brass; the others were heavy Bakelite disks. The reflectors, in turn, were attached to the end of a heavy brass rod which extended horizontally from the loaded carriage of a small lathe bed. The lead screw, which was cut by Mr. David

Mann, has a pitch of 1 mm and an effective length of about 55 cm. It was calibrated to 0.01 mm against a certified standard meter bar and the appropriate corrections for thermal expansion were carefully applied.

The frequency of the source was measured by beating its electrical oscillations against those of an intermediate oscillator which, in turn, could immediately be checked against a standard oscillator. The beat notes were measured with an audiofrequency meter. The standard of frequency was a solid nichrome rod in a separate magnetostriction oscillator. Its frequency was about 4980, depending on the temperature. It was calibrated several times (to one part in one hundred thousand) against the chronometer in the Harvard Astronomical Laboratory by means of Professor Pierce's permanent apparatus. The temperature coefficient of change of frequency is accurately known from Professor Pierce's work. The tuning adjustment of the standard oscillator was fixed and remained unchanged. The intermediate frequency was also derived from a magnetostriction oscillator by means of Professor Pierce's series of nichrome rods which were available at intervals of 1000 cycles from 25,000 to 60,000. By bracketing the unknown frequency (or an harmonic) with two different intermediate frequencies (or harmonics), the errors in setting the audiofrequency meter were neutralized as much as possible.

The source of sound, the oscillators and amplifiers, the reflector and its lead screw, and the standard frequency oscillator were placed in a room in the sub-basement of the Cruft Laboratory. This room is fitted for acoustical research by having its walls, floor and ceiling covered with asbestos felt. This felt lining not only reduces the reflections of sound from the covered surfaces, but also serves as a stabilizer of temperature and humidity. The observing meter system, the control of the lead screw, and the paraphernalia for the measurement of the frequency were placed in the adjoining hallway. The temperature in the room was read on a long mercury thermometer by means of a telescope pointing through a hole in the wall. This thermometer was calibrated against a certified standard kindly loaned by Professor P. W. Bridgman. The relative humidity was deduced from the readings on a wet-bulb thermometer fanned by a small electric fan.

The deflections of the microammeter needle in the vicinity of a reaction, when plotted with respect to the position of the reflector, were symmetrical. The simplest procedure was then to observe the position of the reflector when the microammeter needle stood one or two small scale divisions from the maximum (or minimum), and to turn through the reaction until the needle returned to the same position. The difference between these two recorded readings varied with the wave-length. At 19,790 cycles (wave-length about 17.5 mm) the difference was about 0.8 mm and the accuracy of the mean position about 0.5 mm. At 60,500 cycles (wave-length about 5.7 mm) the difference was about 0.2 mm and the accuracy of the setting about 0.1 mm. These figures are quoted for the case of a two-inch reflector, approximately in the middle of the range over which the determinations of the velocity of sound were made. The settings became slightly more accurate as the reflector approached the source. The observations of the wave-length used in calculating the velocity of sound were averaged for each run by the method described by Professor Pierce.[1]

The values of the velocity of sound were reduced at first to their equivalent values at 20°C and at 87 percent relative humidity (equivalent value at 20°C). During the course of the measurements, the actual relative humidity varied between 71 percent and 77 percent. The equivalent values at 20°C of these limits were 81 percent and 95 percent. Most of these equivalent values, however, clustered about 87 percent. The corrections for the velocity of sound at relative humidities above and below 87 percent were calculated from the work of Reid,[2] who found that a rise of the relative humidity (at 20°C) from zero to saturation increased the velocity of sound to the extent of 0.41 percent. The corrections to the equivalent values at 87 percent relative humidity were so small that any probable inaccuracies of the result stated by Reid did not in the least alter the average. The final average was similarly reduced to its equivalent value at 0°C and (with slight reservations) to a condition of no humidity.

It was furthermore necessary to allow for the

carbon dioxide content of the air in the closed room. Mr. Ralph Hetterly of the chemical laboratory in Harvard College examined a sample of the air, and found the presence of carbon dioxide to the extent of 0.25 percent by volume. In order to reduce the velocity of sound at 20°C to its equivalent value for air free of carbon dioxide, it was necessary to add 0.27 meters/sec. This correction was calculated from data on densities and specific heats given in the International Critical Tables.

The Diffraction Phenomena

The present investigation discloses the fact that the spacing of the reaction points near the source varies with the diameters of both the source and the reflector. In its simplest form the effect is that of an increasing wave-length as the reflector approaches the source. As such, it was observed and discussed by Reid[2] who also refers to the work of other investigators who encountered the effect. Pielemeier[4] also refers to it.

[4] W. H. Pielemeier, Phys. Rev. **34**, 1184 (1929).

A complete series of observations were taken with four sources, one inch in diameter, using each of the five reflectors in turn. In addition, observations were also made with one source, $\frac{5}{8}$ inch in diameter, at approximately 29,000 cycles. The intervals between the observed reactions were taken variously, from one apparent wave-length at 19,760 cycles to 5/2 apparent wave-length at 60,500 cycles. In each case, the observed intervals were about 2 cm long. It was sometimes not possible to identify the positions of the first one or two reactions nearest the source, since the presence of the reflector in such critical positions stopped the oscillations of the source. This was especially true when large reflectors were in use. The observed intervals are represented graphically in Figs. 2–5, each plotted point being accurate to about 0.3 percent. The ordinates are the relative magnitudes of the observed intervals, in terms of their ultimate constant values. The abscissae are the ordinal numbers of the apparent half wave-lengths, counting from the source. The results at 60,500 cycles are not presented,

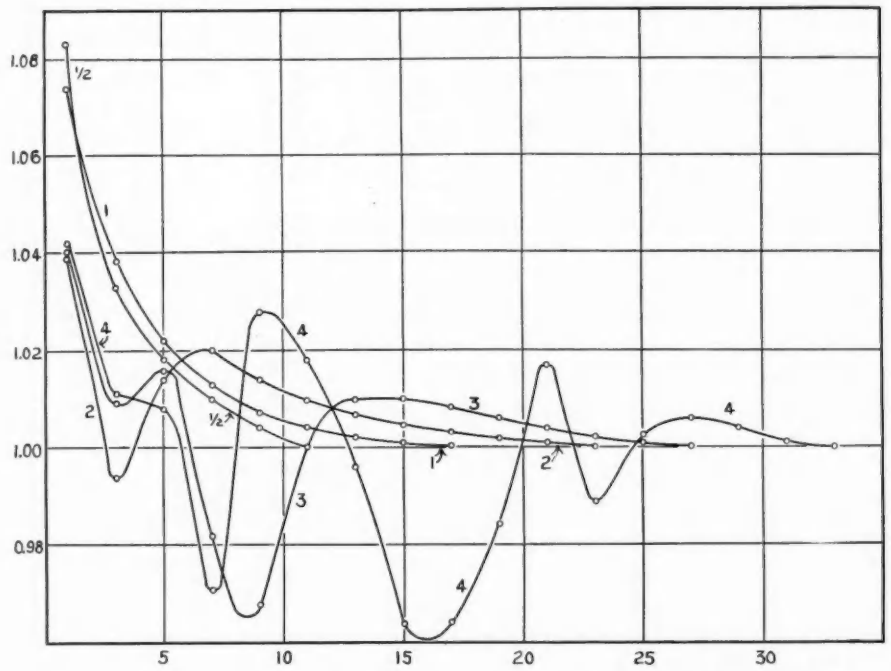

Fig. 2. The relative magnitudes of the observed intervals, plotted with respect to their ordinal numbers counting from the source. Frequency = 19,790. Wave-length (approx.) = 17.5 mm. Diameter of source = 1 inch. Small figures on curves indicate diameter of reflector in inches.

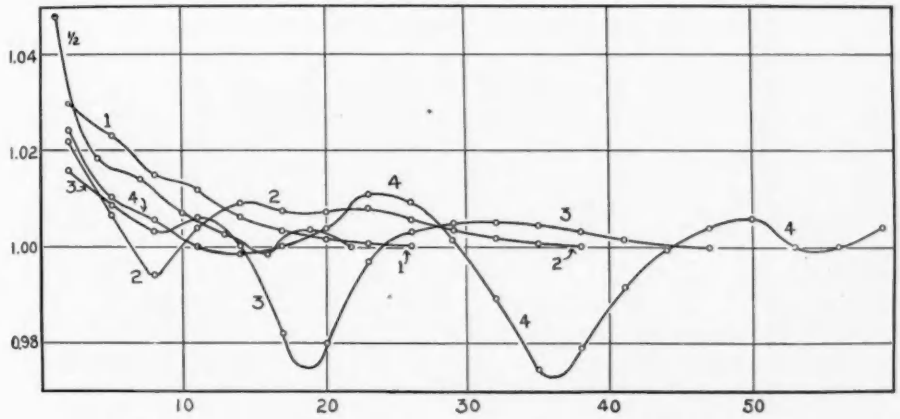

FIG. 3. The relative magnitudes of the observed intervals plotted as in Fig. 2. Frequency = 29,310. Wave-length (approx.) = 12 mm. Diameter of source = 1 inch.

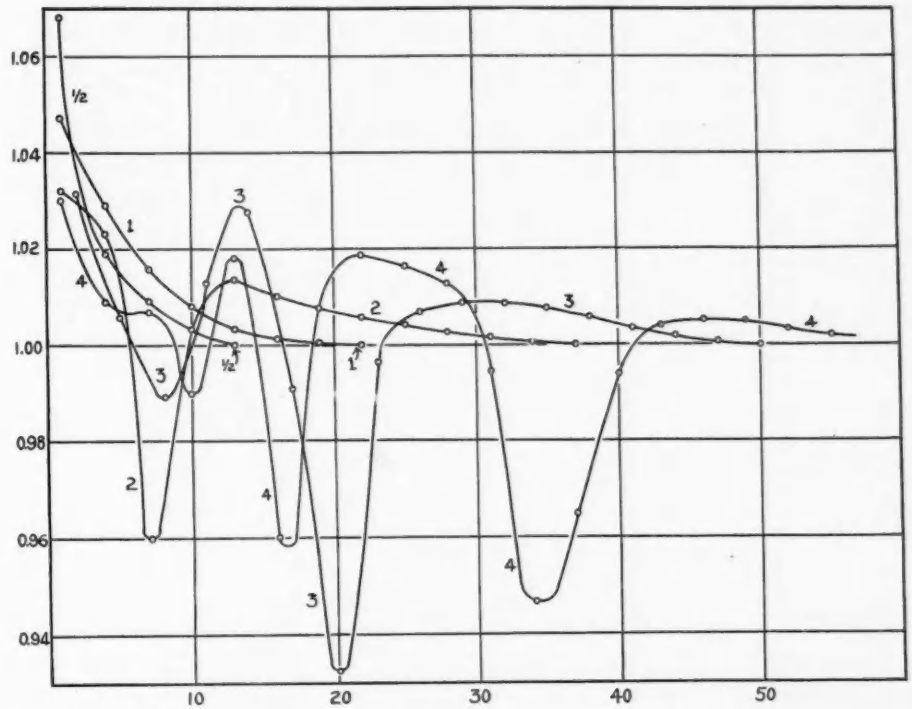

FIG. 4. The relative magnitudes of the observed intervals plotted as in Fig. 2. Frequency = 29,000. Wave-length (approx.) = 12 mm. Diameter of source = 5/8 inch.

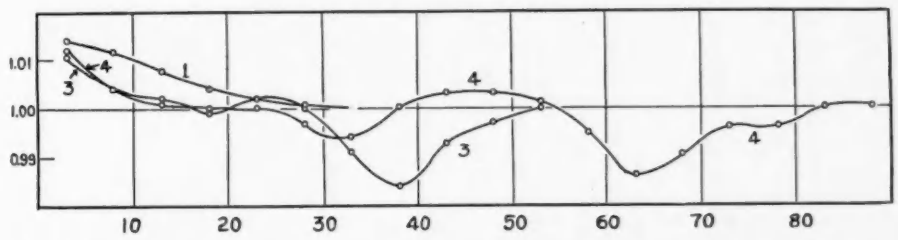

FIG. 5. The relative magnitudes of the observed intervals plotted as in Fig. 2. Frequency = 39,740. Wave-length (approx.) = 8.7 mm. Diameter of source = 1 inch.

since the variations were comparable with the errors of observation.

The results shown in Figs. 2–5 are essentially independent of the form and position of the conical shield round the source. When the angle of the cone is large, the auxiliary wave system between the surface of the flat cone and the reflector causes a noticeable doubling of the reactions. But for cones of any considerable flare, the positions of the reactions are not changed by varying the angle of the cone. The reaction pattern is similarly unaffected by changes in the position of the cone, relative to the face of the source, except when the face of the source is well inside the apex of the cone. In this extreme case, the interval curves (Figs. 2–5) merely show minor depressions here and there. The first order variations remain unchanged.

Before proceeding with the discussion of these results near the source, it is to be noted that the magnitudes of the reactions themselves do not decrease in a regular way as the reflector recedes from the source. If the magnitude of the reactions is plotted with respect to their ordinal numbers, the resulting curves show variations very similar to those of the intervals. It was not possible to study this aspect of the problem since the linear range of the amplifying system was too small to reproduce accurately the large changes of current involved in reactions near the source.

In the cases involving the use of the $\frac{1}{2}$- and 1-inch reflectors, the intervals appear to decrease more or less gradually, until they finally reach their constant values. For larger reflectors, however, this regular decrease of the intervals is modified by the appearance of one or more pronounced minima. These additional variations seem to be intensified by using a smaller source (compare Figs. 3 and 4).

Reid[2] found an approximate relation between the observed wave-length and the distance from the source expressed in wave-lengths. The data given here do not permit of such a simple interpretation. A complete analytical discussion would obviously be very difficult. The situation involves the radiation of waves from a source whose diameter is comparable with the wave-length (and it would probably be necessary to allow for slipping of the air round the edges of the source), the reflection of waves from a finite reflector and, finally, an integration of the phase of the reflected wave over the face of the source to express the condition for the greatest reaction.

Under the assumption that plane waves are exchanged between infinitely large sources and reflectors, the adverse reaction takes place when the phase of the instantaneous displacement velocity in the reflected wave arriving at the source is contrary to that of the wave departing from the source. This assumption results in a system of reactions that are equally spaced at intervals of one-half wave-length.

As a second approximation, one may consider a finite source and a very small reflector, thereby neglecting the diffraction at the reflector. The reactions then occur when the reflector occupies a position at which the instantaneous displacement velocity on the axis is in phase with the instantaneous displacement velocity at the source. This yields the adverse reaction on the source because of the change of phase at the reflector. These positions on the axis may be calculated, after the manner of Crandall[5] with a simple extension, by means of Rayleigh's velocity potential. The velocity potential φ is such a function that the instantaneous displacement velocity in the x direction at any point, $d\xi/dt$, is given by $d\xi/dt = -\partial\varphi/\partial x$. The velocity potential from a pulsating piston is the real part of

$$\varphi = -\frac{e^{j\omega t}}{2\pi}\int\int \frac{\partial\varphi}{\partial n}\frac{e^{-jkr}}{r}\,dS,$$

where dS is an element of the pulsating surface S, r is the distance from dS to the point at which the potential is to be calculated, $-\partial\varphi/\partial n$ is the normal velocity at the surface of the piston, and $k = 2\pi/\lambda$. When this expression is evaluated for any point on the axis of a piston of radius R, at a distance x from the radiating surface, the real part of φ becomes

$$\varphi(x) = \frac{1}{k}\frac{\partial\varphi}{\partial n}\left[\sin(\omega t - k(x^2+R^2)^{\frac{1}{2}}) - \sin(\omega t - kx)\right]$$

$\varphi(x)$ will be a maximum when

$$x = (4m^2\pi^2 - k^2R^2)/4\pi mk,$$

[5] I. B. Crandall, *Theory of Vibrating Systems and Sound*, p. 138, New York, 1926.

where $m=1, 2, 3, 4$, etc. One sees at once that this last expression reduces to $x=m\lambda/2$ for large values of m, i.e., the assumption underlying the argument gives rise to equally spaced reaction points at large distances from the source. The above expression was evaluated and the relative magnitudes of the intervals calculated for all the cases studied. Figs. 6 and 7 show the variations

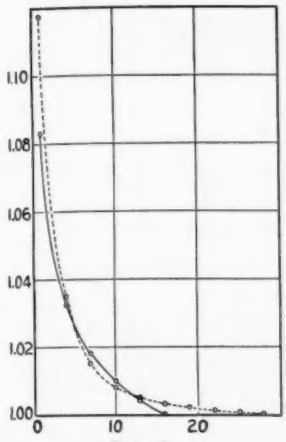

FIG. 6.

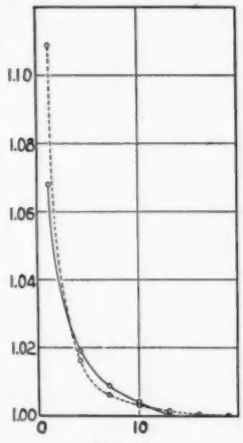

FIG. 7.

FIG. 6. The relative magnitudes of the observed (solid line) and calculated (dotted line) intervals near the source with a ½-inch reflector and a 1-inch source at 19,790 cycles.
FIG. 7. The relative magnitudes of the observed (solid line) and calculated (dotted line) intervals near the source, using a ½-inch reflector and a ⅝-inch source at 29,000 cycles.

of the calculated intervals for two typical cases, that of a 1-inch source at 19,790 cycles and of the ⅝-inch source at 29,000 cycles, together with the corresponding observed intervals with the smallest reflector. Except for the intervals nearest the source, where the assumptions are quite incorrect, the agreement between the observed and calculated values is within experimental error.

The appearance of the pronounced irregularities in Figs. 2–5 is not well understood. It is immediately obvious to suggest a consideration of the diffraction pattern from a circular piston; in particular, to note the difference in phase between the central diffraction maximum and the adjoining secondary maxima and then to identify the appearance of the irregularities with the regions in which the reflector receives energy in one or more of the secondary maxima. To this end, the necessary calculations were made on the basis of Lommel's[6] prodigious treatise on Fresnel diffraction from a circular aperture. These calculations showed that even the largest reflector was too small to intercept any of the secondary maxima, except when it was within four or five wave-lengths from the source. The phenomenon must, therefore, be associated with changing phase of waves within the central diffraction maximum.

[6] E. Lommel, Abhndl. d. bayr. Ak. Wiss. **XV**, 233 (1886).

DETERMINATIONS OF THE VELOCITY OF SOUND

The irregularities in the spacing of the reactions disappear at relatively large distances from the source. The location of the threshold of this region in which the observed wave-length is constant depends on the wave-length, the diameter of the reflector and, in all probability, on the diameter of the source.

The observations in this region were begun at various distances from the source. At 19,790 cycles the threshold of the measurements was taken, at various times, over the range of 34–115 half-wave-lengths (corresponding to 325–948 mm) from the source. At 70,000 cycles, the range was 140–220 half-wave-lengths (330–549 mm). In each case, measurements were taken through the entire effective length of the screw. The relative constancy of the observed intervals is illustrated in Table I, which gives the data from a typical run at 29,312 cycles with a 3-inch reflector. The distance from the source to the

TABLE I. *Data from run 260.*

Frequency = 29,312; n is the ordinal number of the observed reaction; s is the position of the reflector on an arbitrarily located millimeter scale; s' is the corrected position; and d is the difference between successive values of s'. The average wave-length in this case is 11.8140 mm.

n	s	s'	d
0	129.42	129.42	29.55
5	158.97	158.97	29.56
10	188.53	188.53	29.55
15	218.08	218.08	29.55
20	247.63	247.63	29.54
25	277.17	277.17	29.57
30	306.74	306.74	29.55
35	336.30	336.29	29.50
40	365.81	365.79	29.52
45	395.34	395.31	29.51
50	424.85	424.82	29.51
55	454.37	454.33	29.52
60	483.89	483.85	29.53
65	513.43	513.38	29.54
70	542.98	542.92	29.53
75	572.51	572.45	

TABLE II. *Summary of the results at six frequencies for three different reflectors. The values given are the velocity of sound (meters per sec.) reduced to 20°C and 87 percent relative humidity (equivalent value at 20°C).*

Diam. of reflector (inches)	Frequencies					
	19,790	29,315	39,740	52,000	60,500	70,000
2	344.46	344.40	344.48	344.39	344.52	344.40
2	344.50	344.48	344.48	344.42	344.53	344.41
2	344.38	344.48	344.48	344.40	344.44	344.49
2	344.44	344.35	344.42	344.54	344.45	344.39
3	344.47	344.58	344.54	344.49	344.37	344.47
3	344.51	344.55	344.47	344.48	344.52	344.49
3	344.50	344.46	344.41	344.45	344.54	344.43
3	344.35	344.44	344.44	344.51	344.46	344.47
4	344.39	344.49	344.43	344.55	344.54	344.55
4	344.48	344.47	344.43	344.58	344.54	344.52
Averages	344.45	344.47	344.46	344.48	344.49	344.46

first observed reaction was 529 mm, the temperature 23.26°C, and the relative humidity 72 percent. At 19,790 cycles, the location of the reactions could not be determined very precisely. The wave-length at this frequency (17.5 mm) is so large that the deflection of the meter changed slowly as the reflector was moved and the reactions themselves were feeble, because of the large inertia of the source. It was, nevertheless, possible to determine the position of the reactions to 0.05 mm. Except at 19,790 cycles, all the runs to be cited below involved observations at least as consistent as those given in Table I. In most cases, the consistency was greater.

The results of sixty runs, at six frequencies and with three different reflectors, are summarized in Table II. The given results are the velocity of sound reduced to 20°C and 87 percent relative humidity (equivalent value at 20°C). The values of the frequencies at the tops of the columns are approximate. The temperature of the closed room fluctuated through a range of about 2° from week to week, causing small changes in the frequencies of the sources. The tuning adjustment of the oscillator also affected the frequencies slightly. During any one run the temperature remained constant to within 0.02 or 0.03°C, so that the frequency for the run could be determined to one part in thirty thousand.

The averages (cf. Table II) of the velocity at different frequencies show no systematic variation with respect to frequency. The additional runs, using the $\frac{5}{8}$-inch source at 29,002 cycles and the 3-inch reflector, yielded values at 344.44, 344.47, and 344.47 m/sec. The average value from the sixty-three runs is 344.47 m/sec. By adding the correction for carbon dioxide, this is raised to 344.74 m/sec. The equivalent value thereof at 0°C (leaving the relative humidity at 87 percent for the moment) is 332.77 m/sec. The corresponding value in the results quoted by Reid[2] is 332.86 m/sec. The disparity between the two is probably not as large as it would appear. Reid's value at 87 percent relative humidity depends very largely on his results at saturation and these are not consistent. At 42,000 cycles, his value of the velocity of sound is one part in one thousand greater than at all other frequencies and it is clear that these measurements must have been made too near the source. If, in calculating the average, his results at 42,000 cycles and saturation are omitted, the percentage increase of the velocity of sound at 0°C, as the equivalent relative humidity rises from zero to saturation, is changed from 0.41 to about 0.38 percent. Upon making this alteration in the humidity correction, Reid's value for the velocity at 0°C and 87 percent humidity would be 332.79 m/sec. which is to be compared with the value 332.77 m/sec. resulting from this investigation. If this modified humidity correction is applied to the value 332.77 m/sec., the equivalent result for the velocity of sound at 0°C in air free of carbon dioxide and water vapor is 331.68 m/sec.

Despite the fact that the amount of carbon

dioxide in the air of the closed room was greater than the usual content of open air, there is no reason to suppose that it changed very much. The room was closed at all times except when it was necessary to enter for changes in the adjustments of the apparatus. There were no possibilities for any circulation of air.

It is reasonable to assume that the temperature was known to 0.03°C. Whenever the door had been opened, the apparatus was left running for at least an hour before measurements were begun. This eliminated temperature gradients in the room to a large extent and it produced a marked improvement in the consistency of the data. The uncertainty of the temperature reading entails an error of about 1.5 parts in thirty thousand in any one determination of the velocity. The wave-lengths and frequencies were known to one part in thirty thousand. The relative humidity must be given a latitude of at least one percent; and this introduces another error of about one part in thirty thousand. Even if the carbon dioxide content fluctuated through several percent, each individual determination of the velocity still remains trustworthy to one part in three or four thousand. The accuracy of the average, reduced to its equivalent value under standard conditions, cannot be stated with assurance because of the uncertainty of the humidity correction.

It follows that the velocity of sound is independent of the frequency through the range from 20,000 to 70,000, concerning which there has been some doubt, as well as through the range of higher frequencies studied by Reid. It has also been shown under what conditions consistent measurements of the velocity may be made; and there is a numerical value for the velocity that agrees well with previous measurements of precision. Finally, a beginning has been made into the investigation of the apparent anomalies near the source which had hitherto not been studied in detail.

The author acknowledges gratefully his indebtedness to Professor G. W. Pierce under whose guidance this investigation was carried out.

A Logarithmic Recorder for Frequency Response Measurements at Audiofrequencies*

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(Received May, 1933)

THE term *frequency-response characteristic* is employed in the general sense of denoting the steady-state relationship between the transmission or transductance of an electrical or acoustical system and the frequency of the electrical or acoustical excitation. Such characteristics play an important part in the development, testing and maintenance of many types of electrical and acoustical apparatus. With a large class of apparatus the frequency characteristics are sufficiently smooth to permit the curve to be quickly constructed from measurements by the ordinary point-by-point method employing relatively large frequency intervals. In other cases the characteristics are so irregular and serrated as to require a prohibitively large number of measurements for their accurate delineation by this method. Examples of this are loudspeakers, telephone receivers, microphones and electro-mechanical systems in general.

To facilitate obtaining frequency-response characteristics in such cases an automatic recorder has been developed, employing photographic registration, which is capable of rapidly following wide fluctuations in amplitude. It is desirable that both frequency and amplitude scales be logarithmic; the amplitude scale may then be calibrated uniformly in decibels, if desired. In the case of the frequency scale this can be achieved by careful shaping of the plates in the condenser associated with the beat oscillator. A logarithmic amplitude scale presents somewhat more difficulty. The recorder and the method of obtaining logarithmic registration has been described in *Electronics*, January, 1931. The purpose of the present paper is to furnish a more detailed description and to describe several electro-acoustical applications which may be of special interest to members of the acoustical profession.

The logarithmic amplitude recorder also lends itself to measurements involving changes with time instead of frequency. While the present apparatus is not actually designed to make continuous records over long periods of time, the required modifications are easily made. An important application of this kind, which immediately suggests itself, is to the measurement of the decay of sound in a reverberant room. By this means the various types of regular and non-Sabine decay may be quickly and accurately recorded for study. Variations in amplitude in speech and music may also be recorded, particularly the *nuance* in a musical performance. For these applications the utmost recording speed is essential.

FUNDAMENTAL SCHEME

I. Application to Loudspeaker Measurements

The basic scheme may be illustrated by considering a special application—the measurement of the sound-pressure-frequency characteristics of loudspeakers.

Referring to Fig. 1, the loudspeaker is supplied with alternating currents generated by a heterodyne, or beat oscillator. The frequency is continuously variable over a range, in the present instance, of 50 to 10,000 cycles by means of a variable condenser driven by a small motor. An extension of the shaft of this motor is mechanically geared to a platen, carrying the photographic paper, and arranged to move vertically.

* Presented as part of a paper, *Technique of Loud-Speaker Sound Measurements*, Philadelphia Section, Institute of Radio Engineers, May 13, 1931, and at the Annual Convention, Institute of Radio Engineers, Chicago, June 5, 1931; presented at the meeting of the Acoustical Society of America, New York, May 3, 1932.

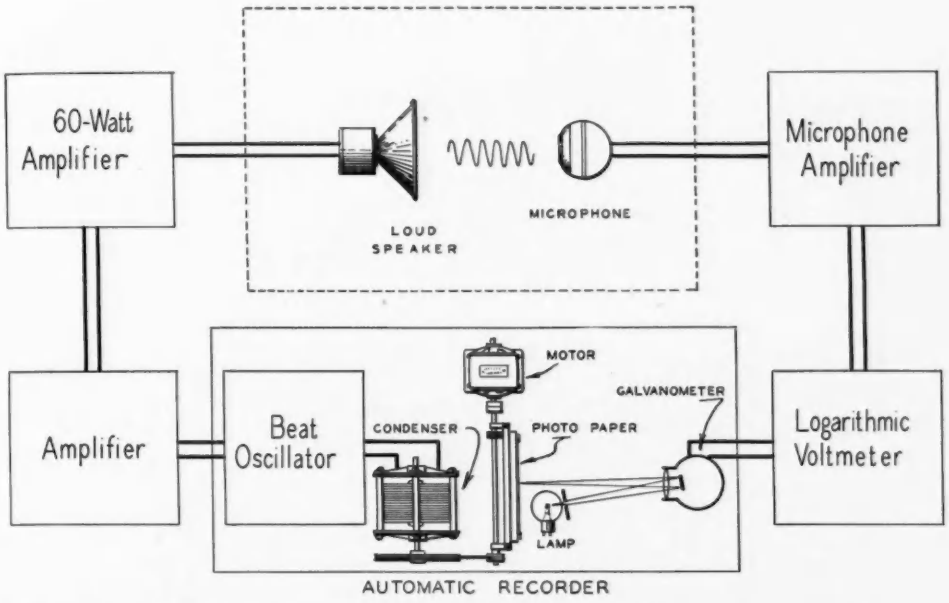

FIG. 1. Schematic diagram of apparatus as set up for automatically recording frequency-response characteristics of loudspeakers.

This provides the frequency axis. The sound from the loudspeaker is picked up by a microphone, amplified and converted into a direct-current which is proportional to the logarithm of the input alternating voltage. This current operates a special galvanometer provided with a mirror which moves a small spot of light across the photographic paper, thus recording the amplitude of the sound-pressure.

A suitable frame of coordinates is impressed upon the bromide paper by projection from a photographic plate in a separate enlarging camera. During this projection the paper is immovably held in a frame which has been carefully aligned for registration with the platen as regards the frequency scale.

Except for the photographic processes, developing, fixing and drying, the recording process is automatic.

The speed of the platen is adjustable over a wide range and is regulated in conformity with the expected serration of the frequency characteristic. The period of the galvanometer and associated apparatus is unusually low so that an ordinary record of loudspeaker response outdoors or in a damped room can be taken in less than one minute. The records, sufficiently dry for inspection and comparison, are available in five minutes, whereas by the point-by-point method several hours would be required.

Several curves may be recorded on one piece of paper. The results of changes in apparatus may be readily brought out by taking, on one sheet, records before and after the change, dotting one curve to facilitate recognition. Means are provided for standardizing the amplifiers so that the interval between two such records on one sheet may be as long as desired.

Photographic views showing the physical arrangement in a laboratory model of the instrument are shown in Figs. 2 and 3. Fig. 2 is a front view showing the control panel.

Particular care has been exercised in the design of the optical system to obtain a fine record. The quality of the record is much superior to those furnished by the conventional types of microphotometric apparatus having similar optical registration. The source of light is a tungsten automobile headlight lamp or a lamp of the type supplied by the General Electric Company for its electrocardiographic apparatus. This lamp is housed at the bottom of the light tube (Figs. 2 and 3) and illuminates a circular aperture (0.010″ diameter) immediately above it. An image of this aperture, one-seventh of this size, is formed at the plane of the

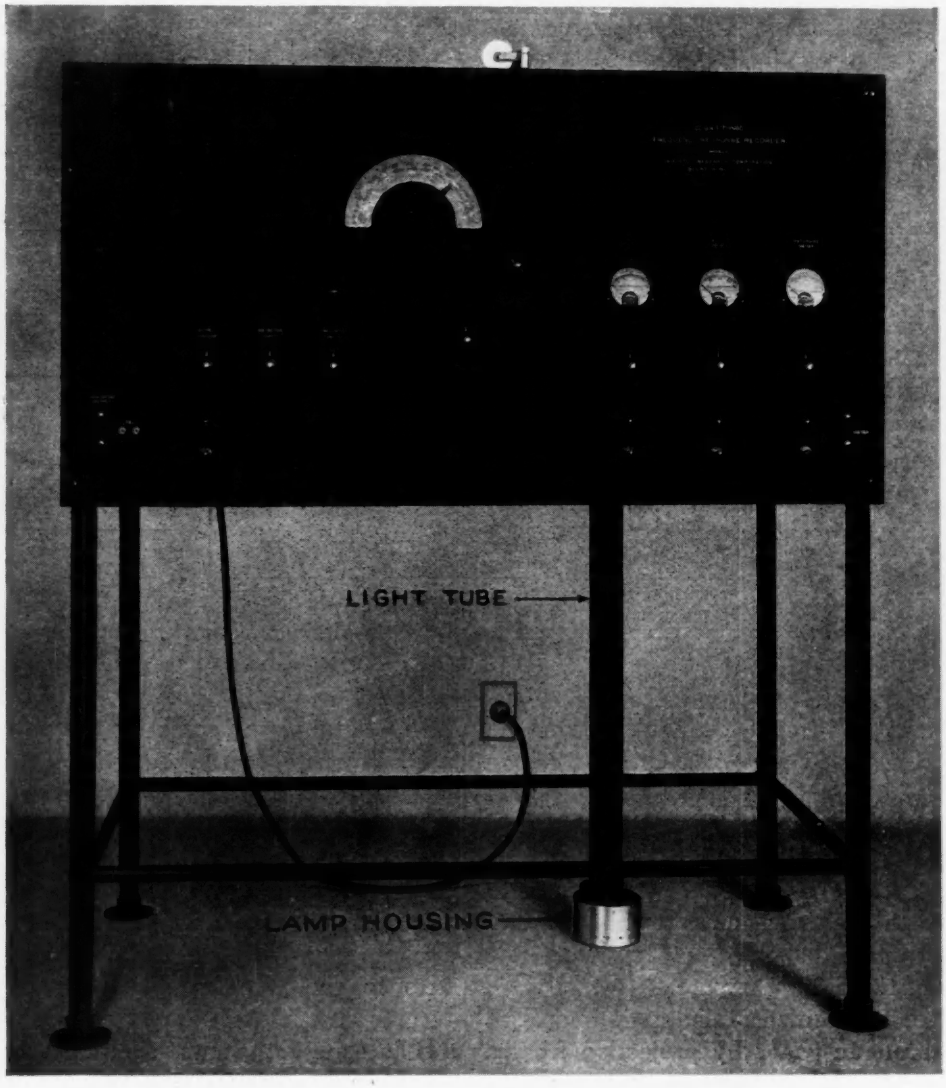

FIG. 2. Front view of logarithmic frequency-response recorder.

photographic paper by means of a lens situated in front of the galvanometer mirror. The light is bent into the horizontal direction by a 45° totally reflecting prism at the top of the light tube. The optical performance of ordinary galvanometer mirrors, silvered on the back, was found quite unsatisfactory. Because of the method of grinding and figuring employed, these mirrors are wedge-shaped and produce a central image accompanied by two satellites, the latter being the result of multiple reflections. A mirror of sufficiently good figure was obtained by silvering the face of a mirror which had been selected as optically plane. On account of the geometry of the optical layout, the lens which is situated in front of the mirror should be free from astigmatism, coma, spherical aberration and chromatism over the actinic range. Fortunately all these corrections, to the order actually required by the geometry of the case, are to be found in a photographic lens. In the apparatus shown one component of a high-grade convertible lens (Bausch & Lomb Protar Series VII) has been employed. The image is so small as to approach to the stellar type characterized by the well-known Airey cone. As a result the

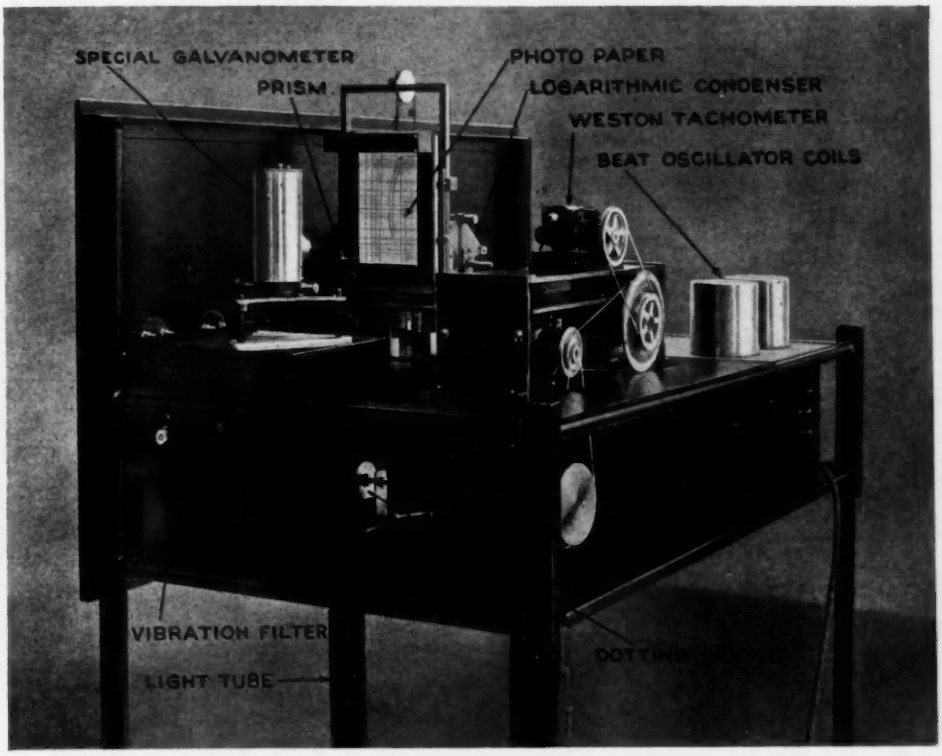

FIG. 3. Rear view of recorder with dust cover removed.

unavoidable variations in the velocity of the beam produce variations in the width of the recorded line rather than in its density, so that a clear record is always obtained.

The curve may be dotted by throwing a rotating segmented shutter into the light beam by means of a key located on the front of the panel.

A vibrating reed, tuned to 65 cycles, provides a frequency fiducial for the precise adjustment of the frequency prior to each record.

The galvanometer was a special one built in the frame of a Leeds-Northrup Type HS instrument. The coil was designed to have a low moment of inertia and was supported by two torque strips, one above and one beneath it. By these means the period was kept at an unusually low value thus permitting the instrument to follow rapid changes without error. The circuits were adjusted to secure critical damping.

II. BEAT OSCILLATOR

The circuit scheme was the conventional one and requires no description. Special care was taken to secure frequency stability in view of temperature changes.

A logarithmic frequency scale was obtained by specially shaping the plates of the variable condenser associated with the variable frequency oscillator. After experimenting with a number of plate shapes the one shown in Fig. 4 was finally adopted. It will be noticed that the stationary plates are quadrantal in shape instead of semicircular. The purpose of this is to avoid the increase in capacity near the zero setting which occurs with semicircular stationary plates because of the approach of the long part of the rotary plates to the edge of the stationary plates. This trouble is completely eliminated with this type of construction, allowing an accurate adjustment of the rate of capacity change near the zero.

The shape of the rotary plates was first determined roughly by calculation, when Kirch-

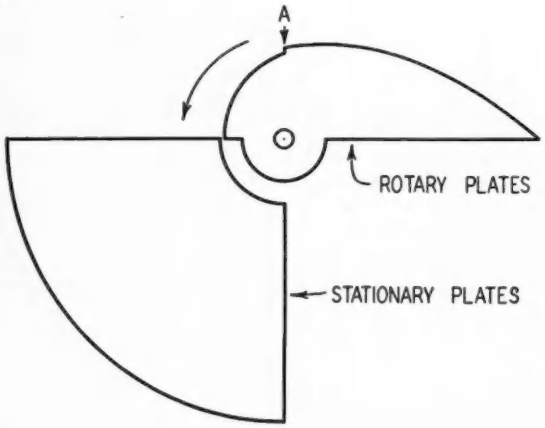

FIG. 4. Illustrating shapes of condenser plates for securing logarithmic frequency variation.

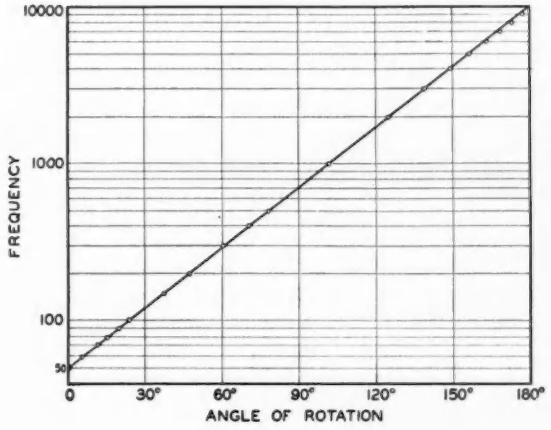

FIG. 5. Calibration of beat oscillator. Generated frequency *versus* angle of rotation of condenser.

hoff's correction for the edge effects was used. The step at A is necessary to insure continuity of the rate of capacity increase as the rotary plates pass through 90° and the entering edge of the rotary plates starts to leave the stationary plates again. After the plates had been cut in accordance with the calculations and assembled it was found that the capacity departed considerably from the required law in the low capacity sector. The rotary plates were then carefully trimmed by filing, starting at zero and working up about 10° at a time, until the required capacity variation was attained. At the low capacity end the capacity is entirely due to edge effect; the rotary plates do not actually enter the stationary plates for the first 40° of their rotation. Although the variation in capacity over this range is only a few micro-microfarads the capacity law must be followed with the same fidelity as at the other end of the scale where the capacity is about one hundred times as great. The precision with which the desired capacity variation can be obtained is indicated by Fig. 5, which represents the frequency generated by the beat oscillator *versus* the angle of rotation of the condenser. A departure of a few percent from a logarithmic variation is shown at the upper part of the scale. This was due to a variation of input tube impedance and has since been remedied.

Provision is also made for *wobbling* the generated frequency. This is accomplished by a small rotating auxiliary variable condenser which is connected to the main condenser through a network for the regulation of the extent of the wobble about the mean frequency. A wobbled frequency has been employed for studying the performance of loudspeakers in reverberant surroundings such as the average living room. Such wobble characteristics are ordinarily not taken below 300 cycles.

III. Logarithmic Voltmeter

This device furnishes a d.c. output current for the operation of the recording galvanometer which is a logarithmic function of the a.c. input voltage over a wide range. This furnishes a scale uniform in decibels and is almost a logical necessity in most kinds of work. The input voltage range of the present apparatus is 100× (40 db), which is adequate for the purposes for which the recorder was designed. Considerably greater ranges may be obtained, however, by the same method if required.

The principle of the logarithmic voltmeter has been described in detail in a previous paper.[1] The basic element is a vacuum tube in which the amplification is an exponential function of the control-grid bias. Several of these *exponential tubes* are arranged in a cascade amplifier, which terminates in a rectifier (Fig. 6). The d.c. output of this rectifier, after the a.c. components have been filtered out, is impressed upon the control grids of the several tubes and automatically

[1] Stuart Ballantine, Electronics **1**, 472 (1931).

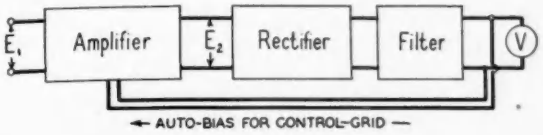

FIG. 6. Functional diagram of method employed in logarithmic voltmeter for securing logarithmic relation between d.c. output current and a.c. input voltage.

varies the amplification in such a way that the output voltage E_2 tends to remain constant regardless of variations in the input voltage E_1. If now the values of the automatic grid bias are indicated by a voltmeter (or ammeter) it can be shown that the deflection of the instrument will be proportional to the logarithm of the input voltage E_1 by virtue of the exponential relation between the amplification of the tube and the control-grid bias.

The exponential relationship between amplification and control-grid bias in the amplifier tube is obtained by an application of the recently discovered variable-mu principle[2] of tube construction which makes it possible to obtain plate-current grid-voltage characteristics of a wide variety of shapes differing from the conventional 3/2 power law of ordinary tubes. This principle may be briefly explained with the aid of Fig. 7. The pitch of the control-grid, instead

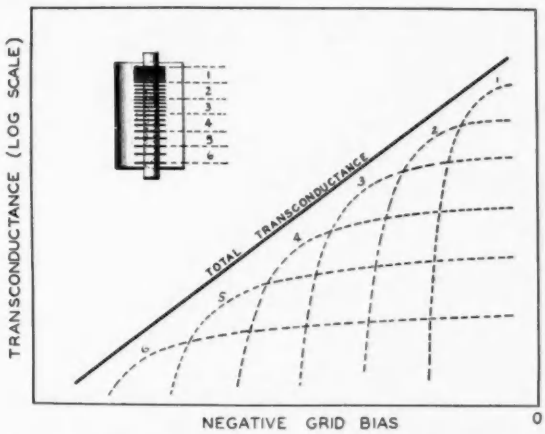

FIG. 7. Illustrating principle of exponential variable-mu tube.

of being uniform, varies along the length of the cathode. The tube may be regarded as being made up of several elementary tubes, 1, 2, 3, ··· connected in parallel. The mu-factors of the elementary tubes decrease progressively from 1 to 6 by virtue of the change in separation of the control-grid wires. At a highly negative control-grid bias the currents from all sections except 6, of lowest mu-factor, are cut off. As the bias decreases the remaining sections come into play progressively at a rate depending upon the geometry, that is, upon the lengths of the sections and their mu-factors. The contributions of the various sections to the transconductance (gain) are indicated by the dotted curves. The solid curve represents the combined effect of all sections and the variation in grid pitch is so chosen as to make this an exponential function of the grid-bias.

The accuracy with which a true exponential characteristic over a considerable range (100×) may be obtained in actual manufacture is shown by the curves of Fig. 8 for two tubes having

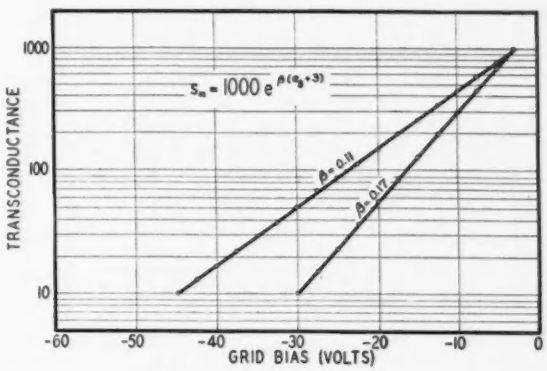

FIG. 8. Transconductance *versus* control-grid voltage for two exponential variable-mu tubes.

different control rates. These tubes are tetrodes and by proper circuit design the amplification of the stage can be made closely proportional to the transconductance.

The actual circuit connections for the logarithmic voltmeter used in the recorder are shown in Fig. 9. Two exponential tubes (Type 551E) are employed. Considerable care is required in the circuit design to avoid relaxation oscillation of the whole system and to prevent a.c. components in the rectifier circuit from being fed back to the control-grids. If a.c. components reach the control-grid they are amplified and affect the overall frequency characteristic of the sys-

[2] Stuart Ballantine and H. A. Snow, Proc. Inst. Radio Eng. **18**, 2102 (1930).

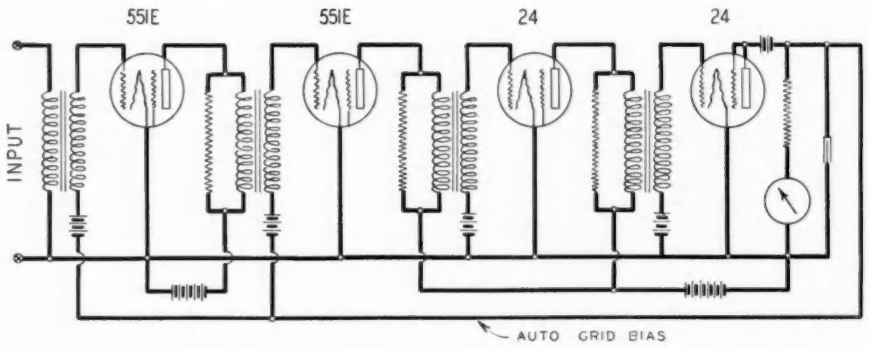

FIG. 9. Circuit diagram of logarithmic voltmeter.

tem. This effect will change with the input level. The necessary and sufficient condition for the avoidance of relaxation oscillation is that any increase in input level shall not produce a rectified current tending to *increase* the amplification and *vice versa*. The rectified current produced under these conditions must always tend—and promptly—to reduce the amplification. Among other things it is necessary to properly phase the impulses delivered to the two grids by the automatic bias by inserting a transformer between the exponential tubes and reversing its connections. The time constants throughout must be adjusted so as to discourage the transient voltage at the rectifier set up by a change in input level, or disturbance at the input, from oscillating, i.e., reversing sign. If this occurs the rectifier acts on the reversed part of the cycle and delivers to the grids a voltage which tends to change the amplification in the wrong sense.

The design difficulties, due to these effects, increase rapidly as the lower limit of the operating frequency range is decreased. In general the lower this limit the slower the speed, or for a given speed the worse the fidelity (frequency characteristic). The speed can be considerably increased by increasing the frequency by heterodyning and filtering. The suppressed carrier system of modulation has been found convenient for this purpose. Since the speed of the recording galvanometer can be increased as much as desired, the ultimate limitation in the speed of recording is that of the voltmeter. By means of a frequency conversion to $20{,}000+f$ cycles and by the use of a vibration galvanometer the

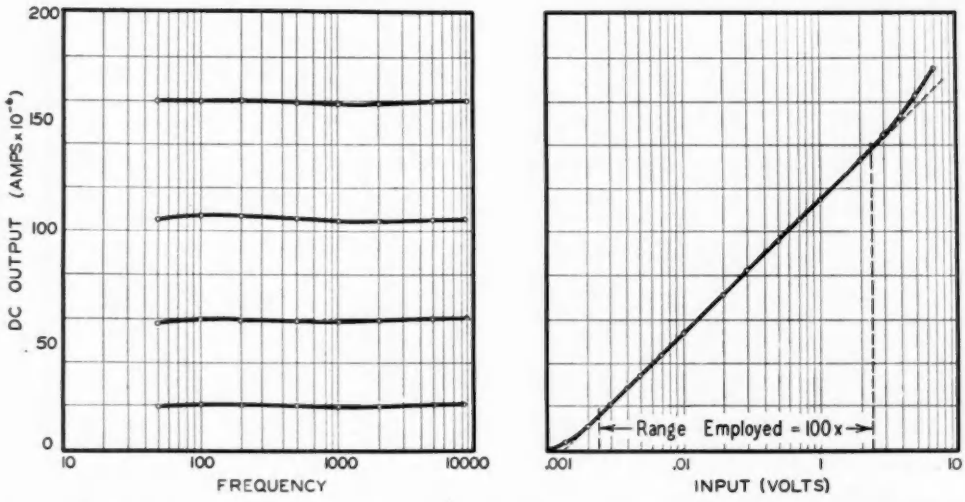

FIG. 10. Characteristics of logarithmic voltmeter; (right), d.c. output current *versus* applied a.c. voltage; (left), d.c. output current *versus* frequency, constant applied voltage.

recording period can be reduced to 1/200th second. This is more than ample for the accurate recording of time effects. There is no point, of course, in reducing the period below that of the lowest frequency component in the signal to be recorded.

In the present apparatus, with a 50-cycle lower limit, the period is about 1/10–1/20th second. This is ample for frequency response recording and also for recording most time changes.

The satisfactory overall performance of the device is shown by the two curves in Fig. 10. The right-hand curve represents the amplitude calibration, which is seen to be accurately logarithmic over the range employed (100×). The left-hand curve represents the "fidelity" at various input levels. This is the relation between d.c. output and frequency for a constant sinusoidal impressed voltage.

It should be pointed out that on account of the action of the rectifier employed, the instrument tends to indicate *maximum* rather than the *rms* values. There is no objection to this for the present application to frequency-response measurements where single sinusoidal voltages are involved, but for other purposes requiring the registration of *rms* values (e.g., noise measurements) a square-law rectifier would be required.

APPLICATIONS

IV. Loudspeaker Measurements

The recorder is particularly useful, in conjunction with a precision condenser microphone, for steady-state sound-pressure-frequency measurements of loudspeakers. To avoid correction for the variation of microphone response with frequency and to record directly the true pressure in the undisturbed sound field the microphone has been designed and equalized so that the wave response[3] is uniform over the frequency range (see Fig. 14).

The best acoustical conditions for sound-pressure frequency measurements of loudspeakers are found outdoors, the speaker and microphone being at a sufficient distance (*ca.* 30 ft.) above the ground to minimize the effects of reflection. The separation of speaker and microphone should be great enough to avoid errors due to diffraction, considering both the dimensions of the radiating surface and those of the cabinet. The procedure which I employ is to take records with the microphone *fixed*, on the axis and at various azimuthal angles, the distance being maintained constant. This furnishes all the information required.

Typical loudspeaker sound-pressure records, taken outdoors under these conditions, are reproduced in Fig. 11. This set of records is incidentally of some historical interest as depicting the development and improvement in the frequency characteristics of loudspeakers which has taken place during the last decade.

Curve 1 represents the response of an early coil-driven horn type speaker (Magnavox, 1921).

Curve 2 relates to a Western Electric 518W horn-type speaker (1922) driven by a balanced armature type of unit. This represents a considerable improvement over (1) with regard to the smoothness of response.

The next development step was taken (1924) by Western Electric Company and is represented by their 18″ cone speaker, Type 540AW. Curve 3 represents the response of this device. While the response was not particularly smooth the frequency range was considerably increased.

A most important advance was next made by Rice and Kellogg who combined the coil-driving principle used in the early Magnavox horn with a conical piston employed as a direct radiator of sound. This speaker (Model 104) was placed on the market about 1926 by Radio Corporation of America. The response characteristic is shown by curve 4. The depression between 2000 and 3000 cycles is characteristic of an acute cone[4] as employed in this model.

Further improvements in the Rice-Kellogg speaker have taken place since 1926, principally as a result of studies of cone materials, methods of coil construction and coupling, geometry of the cone and so forth. Curve 5 represents one of the best speakers of this type appearing during 1931.

[3] Stuart Ballantine, J. Acous. Soc. Am. **III**, 319 (1932); Phys. Rev. **32**, 988 (1928); Proc. Inst. Radio Eng. **18**, 1206 (1930).

[4] H. Stenzel, Elek. Nach. Tech. **7**, 87 (1930).

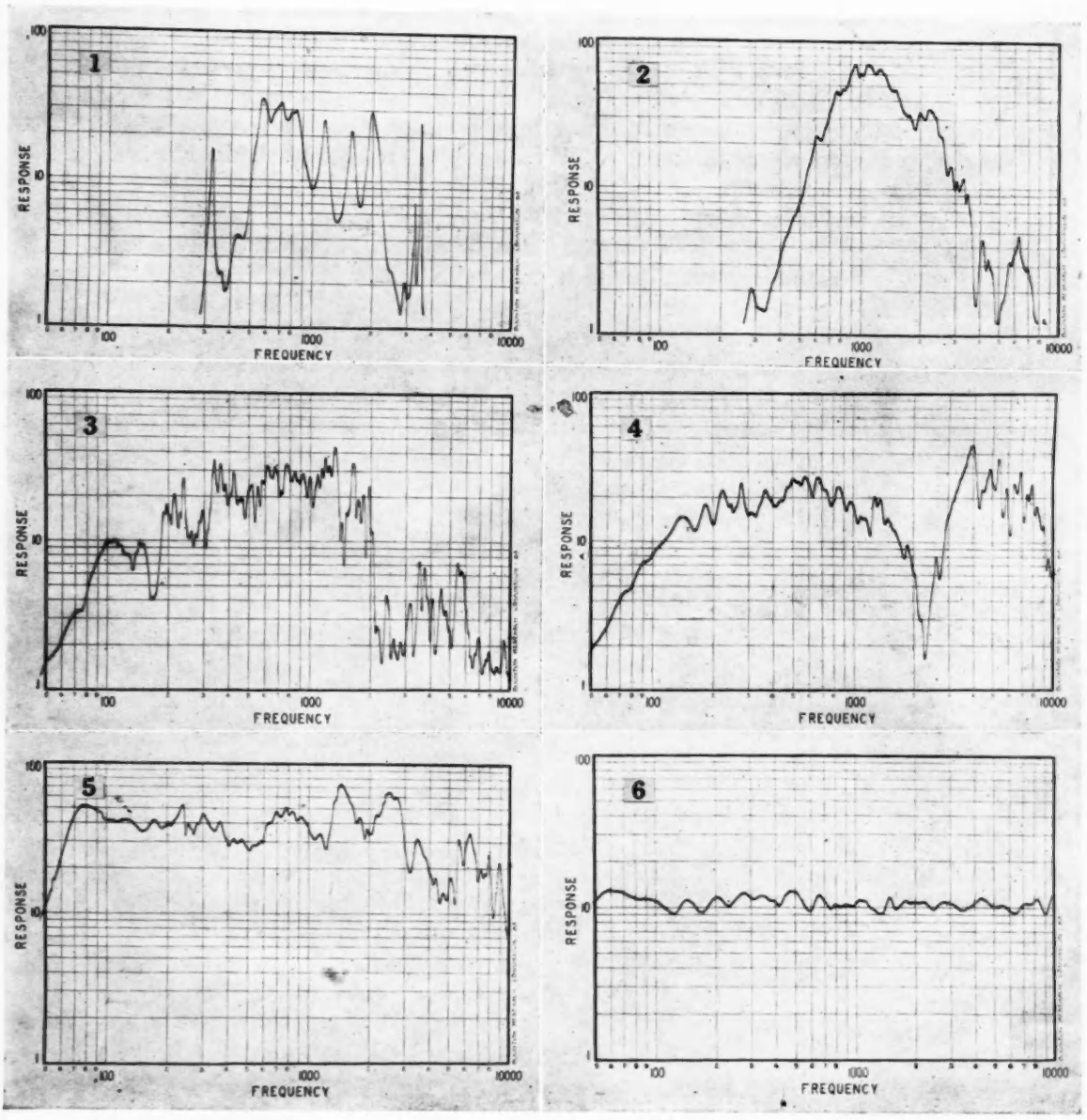

FIG. 11. Records of outdoor frequency-response characteristics depicting ten years' progress in loudspeaker development. (1) Magnavox, coil-driven horn, 1921. (2) W. E. 518W horn type, 1922. (3) W. E. 540AW cone type, 1924. (4) Rice-Kellogg coil-driven cone, RCA Model 104, 1926. (5) Rice-Kellogg speaker of 1931. (6) BRC Model 2 Electrophone, 1932.

Curve 6 represents the response of a BRC Model 2 Electrophone, recently developed here for monitoring purposes in broadcast studios. This is a composite speaker comprising two reproducing units. Frequencies up to 1500 cycles are reproduced by means of a high-grade direct-radiating cone specially designed for this range. Frequencies above 1500 cycles are reproduced by means of a small exponential horn, driven either by a coil or Rochelle-salt crystal. The power is sharply divided between the two units at 1500 cycles. For practical purposes, so far as the ear is capable of judging, the reproduction furnished by this instrument is perfect.

Acoustical measurements out-of-doors are generally made difficult by the presence of wind unless a suitable wind screen is available. Under these conditions the deflections of the sound-pressure meter are unsteady and it is almost impossible to judge by eye when a bona fide indication is being obtained. The recorder has proved of considerable value in furnishing frequency-response curves under unfavorable wind conditions. The procedure merely consists in repeating the recording several times on the same sheet. Unless the wind is continuous the probability of securing a faithful indication at each frequency during at least one of the runs is sufficient to clearly indicate the true characteristic. Usually three records are sufficient for moderately gusty winds.

While curves taken under perfect conditions outdoors are of value as indicating the performance of the loudspeaker *per se*, loudspeakers are rarely used under such conditions and when they are taken indoors into a small room their performance is profoundly modified by the acoustical properties of the room. In these circumstances the room may be properly regarded as acoustically a part of the loudspeaker. Studies of the performance of loudspeakers in the actual reverberant surroundings encountered in a small room are therefore of the utmost importance. In rooms of normal size and reverberation the steady-state is quickly reached at most frequencies so that steady-state frequency response measurements are still of some significance. In making such measurements it is found that the sound-pressure at any point in the room fluctuates widely with frequency making it virtually impossible to construct the curve in the ordinary way by point-by-point measurements. It is here that the recorder finds one of its most useful applications, and is in fact almost indispensable for such investigations.

Typical sound-pressure records for a loudspeaker in a living room ($30' \times 15' \times 12'$) of average reverberation are shown in Fig. 12. The increasing effect of reflections as the microphone is moved away from the loudspeaker will be noticed.

It is also observed that the frequency characteristic changes with the position of the microphone and the loudspeaker in the room, particularly at the lower frequencies.

As a result of living room studies it has been concluded that it is doubtful if satisfactory reproduction of the lower frequencies can ever be achieved in a small room no matter how good the loudspeaker may be. Room resonances (*eigen*-frequencies) completely dominate the picture at these frequencies.

This apparatus has also been used to record the overall electro-acoustic performance of radio broadcast receivers. In this case the beat oscillator modulates a radiofrequency standard signal generator which is connected to the antenna-ground terminals of the receiver through an artificial antenna. The procedure is the same as in loudspeaker measurements.

V. Telephone Receiver Measurements

Another useful application of the recorder is to the measurement of the frequency-response characteristics of telephone receivers. For this purpose the telephone receiver is coupled to the condenser microphone by means of an "artificial ear" designed to present to the receiver the same acoustical impedance conditions as are present when the receiver is held to the average ear. The condenser microphone indicates the pressure in the space representing the auditory canal. For this purpose the pressure response[3] of the microphone is of significance and to avoid the necessity for correcting the records equalizers should be provided to make this uniform over the frequency range.

A typical telephone receiver record is shown in Fig. 13. This shows the pressure response of one receiver of a Western Electric 509W headset

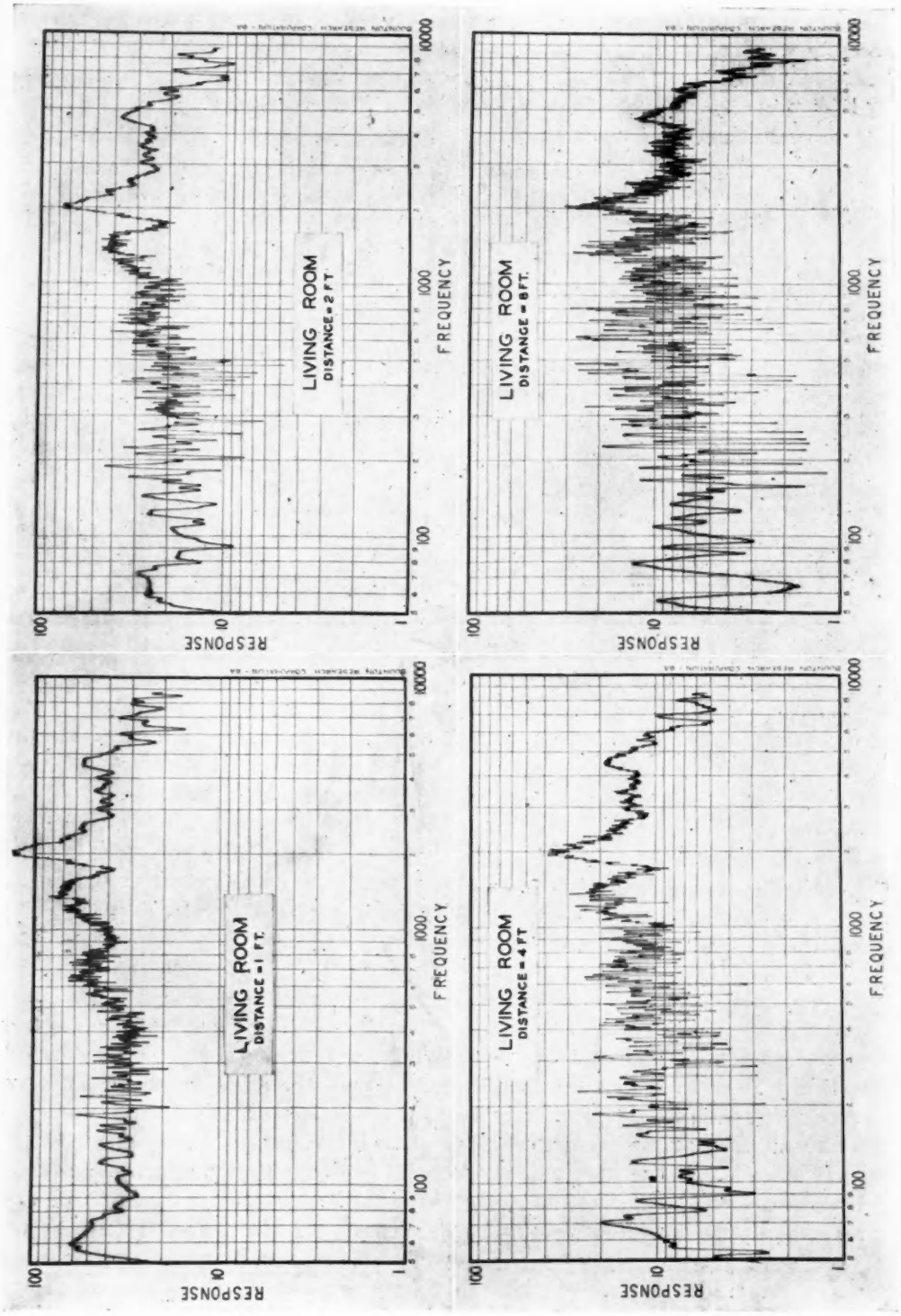

FIG. 12. Frequency-response records of loudspeaker taken in living room of average reverberation.

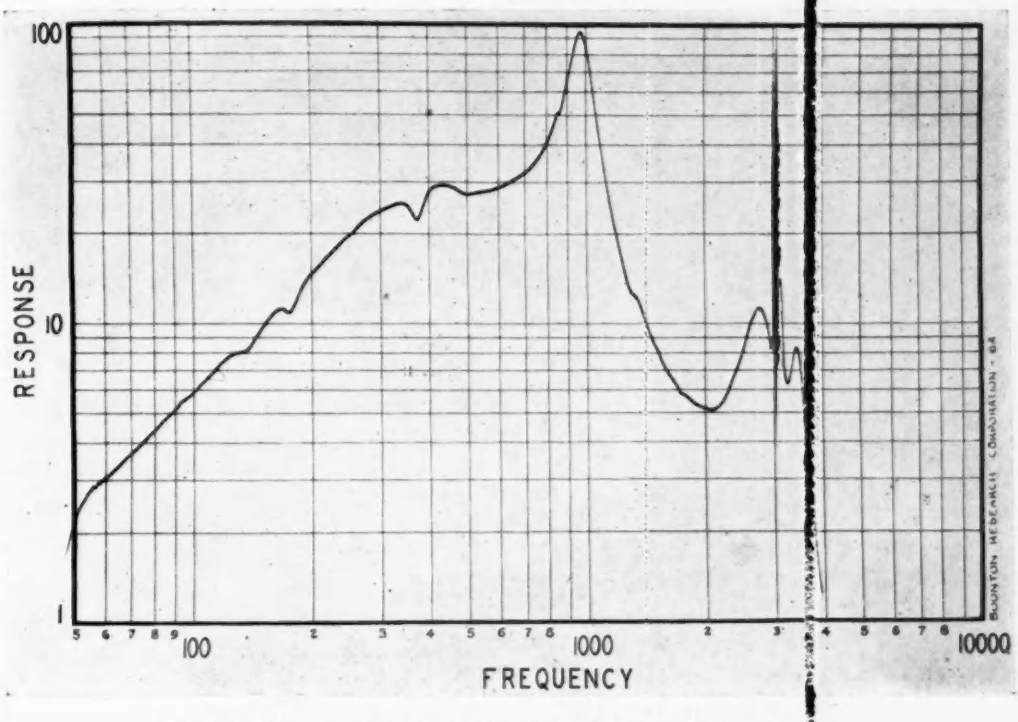

FIG. 13. Response of receiver of W. E. 509W headset on artificial ear.

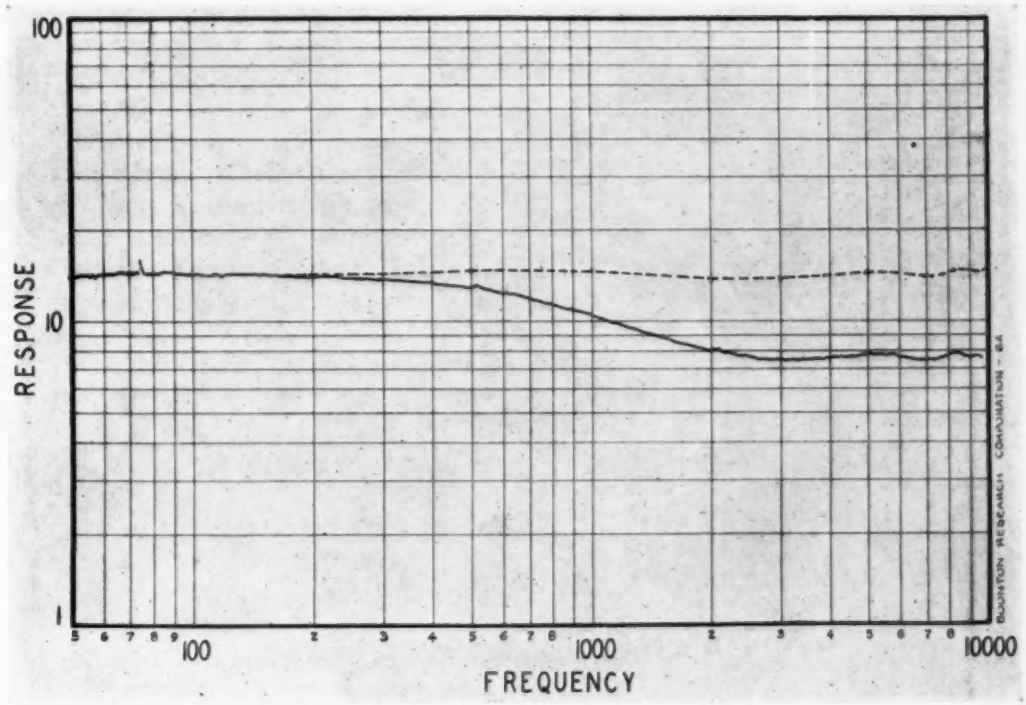

FIG. 14. Record of pressure response of precision spherical condenser microphone, driven by electrostatic grille; dotted curve represents wave response from Rayleigh disk calibration.

supplied at constant voltage through 10,000 ohms. The artificial ear was patterned after that used by the British Post Office,[5] based upon measurements of ear impedances made by West.[6] It also included an acoustical leak to simulate the leakage due to imperfect contact between the receiver cap and the ear.

VI. Microphone Calibration

Another application of this apparatus which is of interest is to recording the pressure response of condenser microphones. For this the electrostatic grille method of excitation[7] is convenient since the applied acoustical pressure is independent of the frequency and can be maintained constant over the frequency range simply by maintaining a constant voltage on the grille.

A record of the pressure response of a precision spherical microphone used for loudspeaker recording is shown in Fig. 14. The wave response for normally incident sound, as determined by means of the Rayleigh disk, is also shown (dotted curve). As mentioned above this microphone has been designed and equalized so that the wave response is uniform.

A wave calibration, sufficiently accurate for most purposes, can be obtained by comparing the unknown microphone with a standard microphone for which an accurate Rayleigh disk calibration is available. The recorder is very valuable in this sort of work. A record is first made, with a suitable source of sound, of the response of the unknown microphone; the standard microphone is then substituted at precisely the same point in the sound field and another record made on the same paper. The response of the unknown microphone can be obtained very simply from these records by means of a pair of dividers. Since the records are continuous a large number of points may be used and an accurate comparison obtained.

Fig. 15 shows typical records obtained in a wave calibration of a Western Electric Type 618A microphone by this method. The wave calibration is shown at the bottom, dotted curve. The solid curve represents the response of the 618A microphone and the dotted curve that of the standard microphone.

VII. Transmission Through Screens

The transmission of sound through fabrics, partitions, screens, etc., can be determined by the same method. A record is first made, with a suitable sound source, without the screen; a second record is then made on the same sheet of paper, with the screen interposed. The transmission is determined as before by measuring the difference between the curves with a pair of dividers.

VIII. Phonograph Pickup Characteristics

The frequency-response characteristics of phonograph pickups may also be determined by driving the needle-point at constant velocity and recording the generated voltage. The stylus is driven by an electromechanical vibrator consisting of two coils similar to those employed in "dynamic" loudspeakers. A small piece of iron rigidly attached to the vibrator close to the needle-point is in inductive relation to two coils mounted on a permanent magnet. The voltage induced in these coils is proportional to the velocity of the needle-point and serves to measure the applied velocity. If the driving coils are supplied with constant current it is found that the needle-point velocity varies considerably over the frequency range because of variations in mechanical impedance. To overcome this inconvenience and to secure a constant velocity, an automatic control is employed. The output of the velocity indicator is rectified and the rectified current, properly filtered, is used to control the bias of the tubes of the amplifier supplying the driver coils. If the velocity tends to increase, the rectified output increases and thus automatically decreases the amplification cutting down the current supply to the driver coils. In this way the velocity is automatically maintained constant in spite of fluctuations in the mechanical impedance of the pickup device. With this constant velocity drive the recording of phonograph pickup characteristics presents no more difficulty than similar tests of the other devices.

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[5] W. West, Post Office E. E. J. **22**, 260 (1930).
[6] W. West, Post Office E. E. J. **21**, 293 (1929).
[7] Stuart Ballantine, J. Acous. Soc. Am. **III**, 321 (1932).

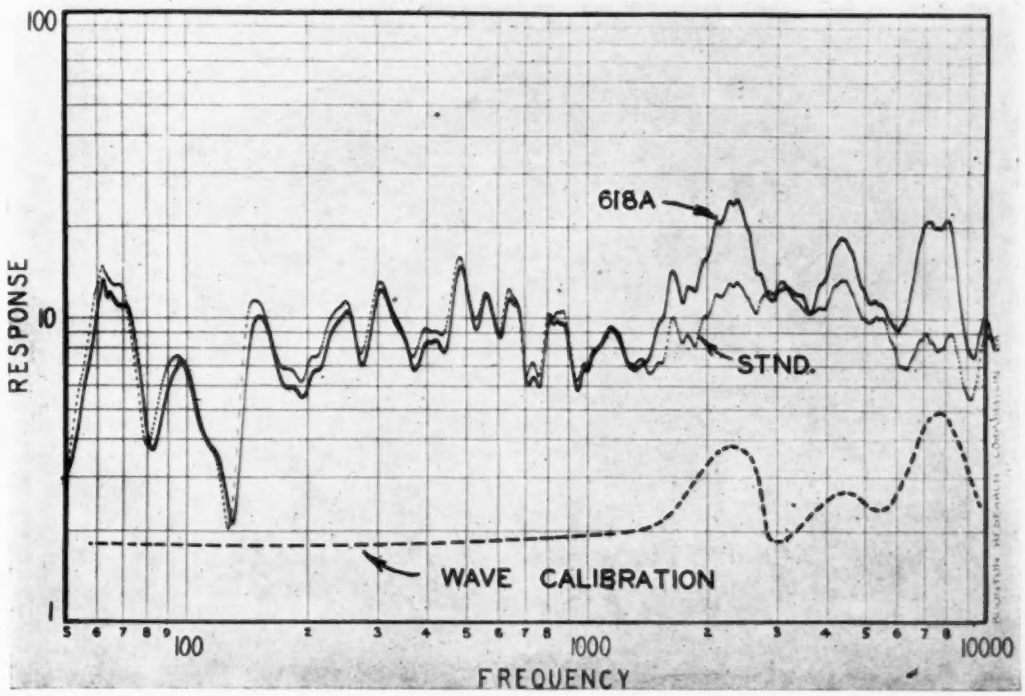

FIG. 15. Records taken during wave calibration of a W. E. Type 618A microphone by comparison method: (solid curve) response of 618A microphone; (dotted curve) response of standard microphone.

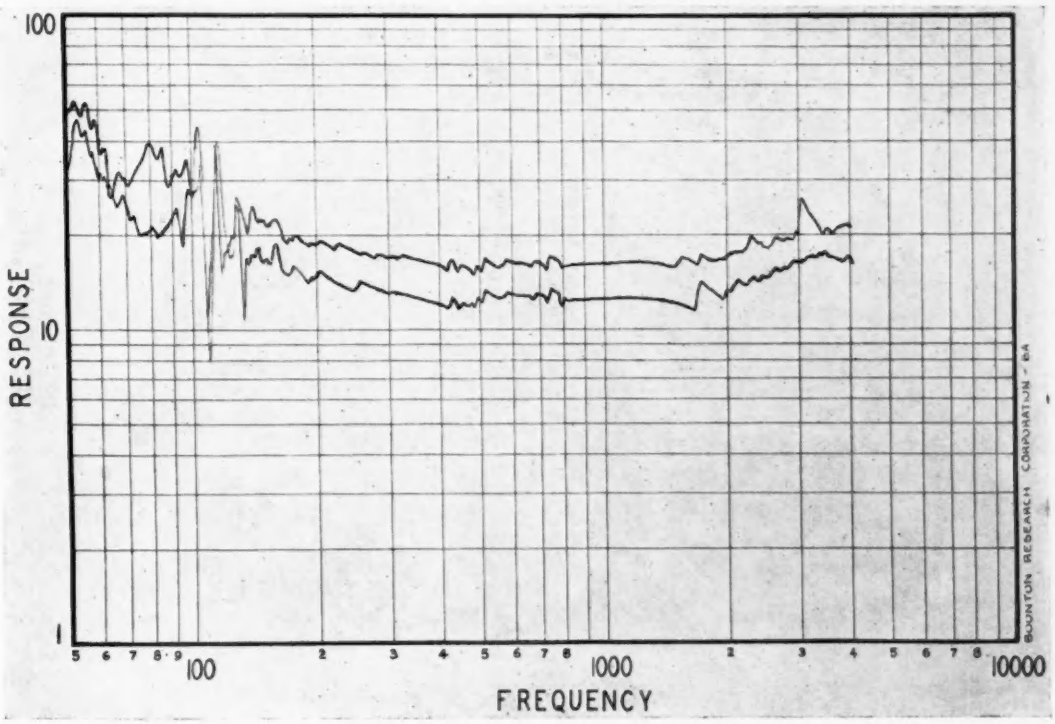

FIG. 16. Record of frequency response of BRC Model 4 oil-damped phonograph pickup mechanically driven with constant stylus velocity.

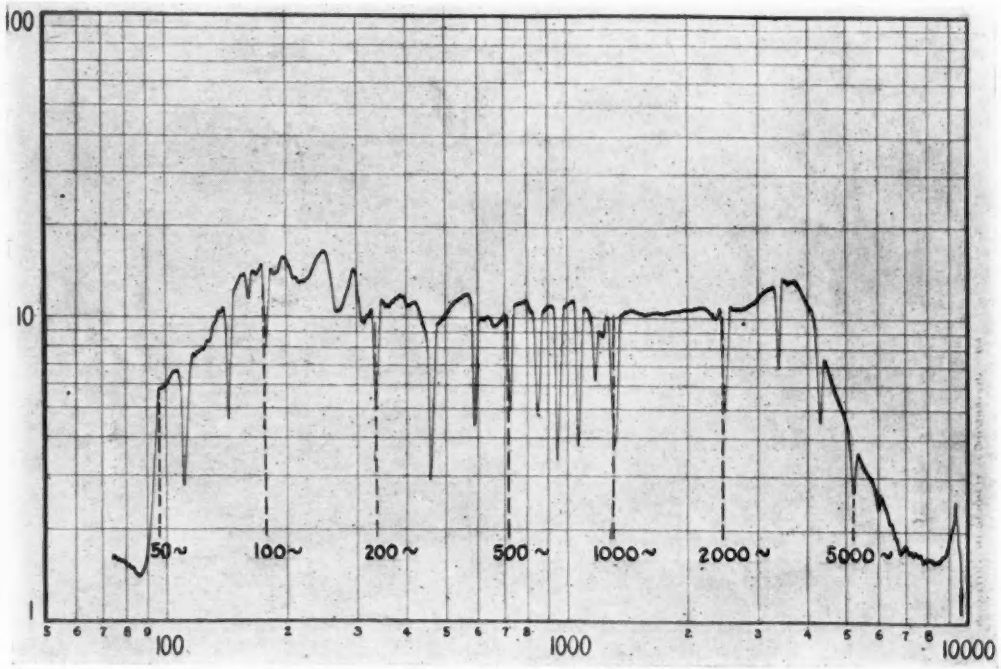

FIG. 17. Overall frequency characteristics of a complete phonograph "system," including electrical cutter, record and pickup.

Fig. 16 represents the response of a BRC Model 4 oil-damped pickup recorded by this method. Two curves are shown representing the effect of a minor change in adjustment. The curves are terminated at 4000 cycles because the indications of the velocity indicator became inaccurate above that frequency. Inertial resonances involving the tone arm are clearly discernible between 100 and 200 cycles.

Response characteristics obtained by mechanical driving do not always agree with those obtained by driving the stylus by means of constant frequency records. The reasons for this need not be discussed here. The most significant data are obtained by means of the record drive; nevertheless the mechanically driven characteristics are of value during development work and considerable time can be saved by automatically recording them.

The recorder is also useful for recording the frequency characteristics from records. In this case the frequency record is cut with a continuously variable frequency, preferably varying as a logarithmic function of time.

Fig. 17 shows the overall frequency characteristic of a complete phonograph "system," that is an electrical phonograph cutter, record and pickup. The frequencies were spotted by interrupting the cutter current while recording on the wax. An approximately logarithmic relation between frequency and time was obtained by operating the cutter by means of the motor-driven beat oscillator of the recorder. The wax was then processed and the record used to drive the pickup. A record was made of the output voltage, the platen speed having first been adjusted to match approximately the duration of the record. The exact frequencies are marked on the curve; the printed frequency coordinates have, of course, no significance.

The Estimation of Fractional Loudness

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(Received May 18, 1933)

CONSIDERABLE divergence exists in the results obtained by different investigators[1, 2] for the reductions in intensity which observers judge to correspond to reductions in loudness of one-half, one-fourth, or other fractions. The investigation being reported was made with the following purposes: (1) To repeat the experiments of previous investigators using an experimental procedure different than those used previously. (2) To explain the discrepancies between the results obtained previously. (3) To determine how judgments of fractional loudness vary with frequency and with loudness level. (4) To compare the accuracy with which an observer would repeat his own readings with the variations in the readings obtained by different observers.

EXPERIMENTAL PROCEDURE

In order that the loudness at the ears of the observer might be known with some degree of accuracy, headphones were used for this series of experiments. The observer was given a switch which could be placed at will on either of two positions which were designated as positions *S* and *X*. The sounds heard with the switch in these two positions will also be designated as *S* and *X*. With the switch on position *S*, the sound from the headphones was predetermined both in pitch and loudness by the operator; with the switch in position *X* the same tone was heard but its loudness could be adjusted by the observer by either one or both of two controls. In order that the judgment of the observer would not be influenced by the position of the controls or the amount by which he turned them, plain knobs without pointers or scales were used. As a further precaution, the operator changed, after each setting made by the observer, the position of both of the observer's controls as well as a third control which was at a distance from the observer's table. The use of the third control not only changed the settings required for a given loudness but also the amount by which the loudness was changed by a given movement of either of the observer's controls.

After the threshold of hearing of an observer was determined the operator adjusted the loudness of *S* to 30 decibels. The observer was then asked to adjust his controls so that sound *X* was equal in loudness to sound *S*. This adjustment gave him some practice in making the required adjustments and gave a measure of the carefulness with which he worked. Next the observer was asked to make *X* one-half as loud as *S*. In making this adjustment he was advised to make the final setting so that it was midway between the settings which he thought gave loudnesses on both sides of the desired value. After the setting was made the operator measured the difference in sensation levels between *X* and *S*, then changed the settings of the three potential dividers controlling *X*. The observer was, of course, informed that the positions of his controls and the amount he turned them had no meaning from one setting to the next.

The observer was then asked to make *X* one-fourth as loud as *S*, then in turn to make *X* one-tenth, one-one hundredth, twice, four times, ten times, and finally one hundred times as loud as *S*. The procedure outlined above was followed for loudness levels of 30, 55 and 80 decibels, and for three sounds, a pure 1000 cycle per second tone, a pure 60 cycle per second tone, and a complex noise made up of over 40 tones with an energy distribution over the frequency range somewhat similar to that of speech. The loudness levels are given in terms of equivalent 1000 cycle loudnesses, taking the 1000 cycle

[1] Laird, Taylor and Wille, *The Apparent Reduction in Loudness*, J. Acous. Soc. Am. III, 393 (1932).

[2] L. B. Ham and J. S. Parkinson, *Loudness and Intensity Relations*, J. Acous. Soc. Am. III, 511 (1932).

TABLE I. *Average changes in intensity corresponding to certain fractional and multiple values of loudness.*

Tone Loudness	*1000 Cycles* 30 db	55 db	80 db	*60 Cycles* 30 db	55 db	80 db	*Complex* 30 db	55 db	80 db
1/100	18.4	36.0	51.5	—	16.6	25.2	18.7	31.7	44.8
1/10	11.6	22.0	30.6	9.2	10.1	16.8	12.4	20.0	27.0
1/4	7.2	14.9	19.6	6.1	6.9	11.6	8.5	14.0	18.7
1/2	4.3	9.4	11.7	4.1	4.9	7.5	4.9	10.4	11.0
1	0.3	0.05	0.5	—	—	—	—	—	—
2	10.6	7.0	9.1	5.6	5.3	6.6	6.2	5.7	8.5
4	16.8	14.2	15.0	10.6	10.5	9.5	11.6	11.9	15.5
10	26.1	24.4	21.8	17.1	16.8	—	18.7	24.2	23.9
100	53.1	44.7	—	30.6	—	—	45.7	—	—
Number of observations		44			31			31	

TABLE II. *Median values of observations.*

Tone Loudness	*1000 Cycles* 30 db	55 db	80 db	*60 Cycles* 30 db	55 db	80 db	*Complex* 30 db	55 db	80 db
1/100	19	36	53	—	15	24	19	32	45
1/10	11	21	31	8.7	10	16	11	20	27
1/4	6.1	14	19	6.5	9.0	11	7.7	14	18
1/2	3.5	8.8	10	3.7	4.7	6.7	5.0	10	12
2	9.5	6.1	8.2	5.0	5.0	6.7	5.5	5.0	7.3
4	16	13	15	9.7	9.5	9.3	10	11	15
10	24	25	22	16	16	—	18	23	26
100	54	46	—	31	—	—	50	—	—

threshold as 0.00053 bar. Kingsbury's data[3] were used for computing the voltage input to the phones. No corrections were made for leakage, so the actual loudness values, at the ear, for the 60 cycle tone are probably somewhat lower than the values given.

Each observer was given as much time as he wished for making each setting. By merely throwing his switch he could listen to the original sound *S* at any time. Care was taken to minimize switching clicks.

EXPERIMENTAL DATA

The results of the measurements are shown in Table I. Each value given represents the average difference in intensity, expressed in decibels, between the original sound *S* and the adjusted sound *X*.

Since there were individual values which depart considerably from the mean values, the median values of the observers' settings are perhaps of as great use as the average values. The median values are given in Table II. A comparison of the mean and median values will serve as a measure of the spread in the corresponding distribution curves. It will be observed that the spread is surprisingly small.

An examination of Tables I and II will show the following facts:

(1) The greater the loudness level, the greater is the intensity ratio between the original sound and the sound judged to be half (or other fraction) as loud.

(2) For sounds of low loudness level, the change in intensity, measured in decibels, is greater when the loudness was doubled than when it was halved. For high loudness levels, the opposite is true. In other words, if observers are first asked to adjust the loudness of a sound to a value twice as loud, then are asked to adjust this sound to a value half as loud, they will not, on the average, arrive at the original sound, but to a value either louder than or less loud than the original sound according as a low or high loudness level was used for the test. The significance of this fact will be pointed out later.

(3) The change, expressed in decibels, corresponding to quarter loudness is in every case

[3] B. A. Kingsbury, *Direct Comparison of Loudness of Pure Tones*, Phys. Rev. **29**, 588 (1927).

TABLE III. *Susceptibility of observers to slight suggestion.*

	1000 Cycle Tone					
	30 db		55 db		80 db	
	Case I	Case II	Case I	Case II	Case I	Case II
1/100	20.0	15.7	37.0	34.0	50.5	47.5
1/10	13.8	11.0	24.1	20.6	34.6	29.1
1/4	9.2	6.6	19.6	13.2	23.8	17.8
1/2	5.0	4.2	11.6	9.3	14.1	11.6

less than twice the corresponding change for half loudness. In other words, if observers are asked to halve the loudness of a sound then to halve the resulting sound they will arrive at a sound of less intensity than if they were asked to quarter the loudness of the original sound.

(4) A given fractional change in loudness as judged by the observers does not correspond to the same fractional change in intensity for sounds of different frequency. The data of Kingsbury[3] show that a given change in the sensation level of a 60 cycle tone corresponds to about double that change in the equivalent 1000 cycle loudness. The data of Table I agree with this very well.

SUSCEPTIBILITY OF OBSERVERS TO SLIGHT SUGGESTION

When the first measurements were being taken it was noticed that each observer would quickly make a rough adjustment which evidently seemed to be fairly satisfactory to him and then he would vary the intensity of the sound X by only a few decibels in making the final setting. When some of the observers were asked to repeat the test, they followed the same procedure but the two ranges over which they worked in making the final setting did not overlap. This seemed to indicate that the reliability of the observations was not as great as each observer seemed to think. It seemed possible that although the first rough adjustment was made almost at random, it greatly influenced the final results.

In order to determine to what extent the observers' judgments were susceptible to suggestion, twenty-four observers were asked to repeat the 1000 cycles readings. The interval between the first test and its repetition varied from two days to six weeks. Slightly different procedures were followed in making the two sets of readings. For Case I, the operator, between readings, adjusted the three controls on sound X so that when the observer first listened to it, it was much fainter than sound S. For Case II, sound X was adjusted so as to be approximately equal to sound S. These adjustments were made only before the settings listed in Table II, at other times, that is, for the multiple loudness settings, these adjustments were made at random. Care was taken that the observer would not be aware that the procedure was varied in the slightest for the two series of measurements. Half of the observers worked under the procedure of Case I first, and half Case II first.

The average results of these tests are shown in Table III.

It will be observed that, for each pair of values, the value under Case I is greater than the value under Case II. Thus it is seen that the observers were influenced by the initial value of X in spite of the fact that they not only listened to the original sound S a number of times during each test but they also adjusted X to values both louder and less loud than the desired value. Since the difference in the experimental procedure was very slight and the suggestion quite indirect it is evident that observers are easily influenced in making their judgments.

It is believed that the discrepancies between the results of Laird, Taylor and Wille[1] and the results of Ham and Parkinson[2] can be partly, if not wholly, explained by the supposition that the judgments of the observers were influenced by the methods used in obtaining the data. The experimental procedure of Laird, Taylor and Wille was briefly somewhat as follows: the original sound was produced for a definite interval and was followed by a test tone of reduced intensity. The observer was asked to state whether the loudness of the test tone was

TABLE IV. *Maximum, minimum, and mean deviation from mean values 1000 cycle tone. Results expressed in decibels.*

Loudness	*30 db* Max.	Min.	Mean dev.	*55 db* Max.	Min.	Mean dev.	*80 db* Max.	Min.	Mean dev.
1/100	28.5	5.7	3.9	62.0	20.3	6.0	77.0	21.3	9.3
1/10	30.0	4.5	3.5	46.3	8.7	6.0	67.0	8.7	10.3
1/4	25.0	1.5	2.7	35.0	1.7	5.2	44.0	4.0	7.2
1/2	14.0	1.0	1.7	20.0	2.3	3.8	26.7	2.0	5.2
2	29.0	3.5	4.2	18.0	1.5	3.3	21.0	3.0	4.8
4	36.0	6.5	5.0	33.5	5.0	4.7	27.0	5.0	4.5
10	65.0	10.0	7.1	50.0	5.5	7.4	40.0	7.0	4.6
100	71.0	21.7	12.1	60.0	16.7	7.7	—	—	—

greater or less than the desired value. The intensity of a test tone was evidently varied over a very wide range, indeed it may be inferred from the published paper[1] that the sensation level of the test sound was sometimes less than half the sensation level of the original sound, the levels being expressed on the decibel scale. It is believed that due to this very great difference between the loudnesses of the original and the test sounds and due to the fact that the loudness of the test sound was varied by five decibel steps, the observers' judgments were greatly influenced in the direction of increasing the intensity ratio corresponding to a given fractional change. Probably if the experiment were repeated in the same way, but with the first test sound kept within 15 or 20 decibels of the original sound and the readings taken with one decibel steps, the results would be quite different. Likewise, if the experimental procedure of Ham and Parkinson were changed only by changing the order in which the readings were taken and the size of the loudness steps, it is believed that their results might possibly be changed.

ACCURACY OF RESULTS

In both of the investigations mentioned above, each group of investigators found remarkable agreement among their own observers, yet there was marked disagreement between the two groups. The writers of this article also observed that almost every observer was quite sure that the required settings could be made and was almost invariably well satisfied with his settings.

The evident feeling of most of the observers that fractional settings of loudness could be made tends to verify the tacit assumption that fractional loudnesses have a definite physical meaning. The satisfaction with which settings could be made was much greater in the case of this series of measurements than it was in the case of another series wherein the observers were asked to set a 1000 cycle tone equal in loudness to a tone of another frequency or to a complex sound. It is interesting to note that the values for the mean deviation from the mean were, on the average, substantially the same for the last mentioned series of measurements as for the fractional loudness judgments. From this fact it appears that a fractional loudness of a given sound has as definite a meaning to the average individual as has the equality of loudness between different sounds.

The consistency with which the various observers agreed and the accuracy of the results may be found by examining Table IV. This table shows the average, the maximum, and the minimum values and the mean deviation from the mean, for the measurements on the 1000 cycle tone. The corresponding values of the 60 cycle tone and the complex sound are omitted in order to save space, but they are quite comparable with the values given.

METHOD OF JUDGING FRACTIONAL LOUDNESS

It seems reasonable that an observer might logically be expected to use any one of three different methods to judge fractional loudness. It might be assumed that a sound would be decreased to half value if the distance between him and the source were doubled. In this case half loudness should correspond to six decibels change, quarter loudness to twelve decibels change and so on. If it were assumed that the

sound of n machines was half as loud as the sound from $2n$ machines, half loudness would correspond to a change of three decibels. The third method which might be used would be based upon the number of perceptible loudness steps between the original sound and the threshold.

An examination of the data shown in Tables I and II makes it evident that the average observer does not use either of the first two methods. However, it might be remarked here that those few observers who stated that they formed their judgments by either of these two methods gave lower than average values. Table V has been prepared to show the values for the change in sensation level corresponding to certain fractional and multiple values of the number of perceptible loudness steps between the original sound and the threshold. The values given in this table were computed from the results given by Riesz[4] for a 1000 cycle tone. It is evident that the agreement with the observed values shown in Tables I and II, is not good and so it may be concluded that perceptible loudness steps are not the basis of loudness judgments.

TABLE V. *Computed values of intensity changes (in decibels) based upon the number of perceptible loudness increments between a sound and the threshold.*

	1000 Cycle Tone		
	30 db	55 db	80 db
1/100	30	53	74
1/10	24	36	50
1/4	17	24	34
1/2	9	12	20
2	12	18	33
4	28	36	—
10	41	—	—

Fletcher[5] has determined by other methods a scale wherein the values are proportional to sensation. From curves plotted from these data the change in sensation level corresponding to the fractional and multiple loudness values used in these tests, have been computed and are given in Table VI.

TABLE VI. *Changes in sensation level corresponding to certain fractional and multiple values as computed from Fletcher's G function.*

	1000 Cycles		
	30 db	55 db	80 db
1/100	25.5	41.2	56.2
1/10	15.4	26.4	33.5
1/4	10.4	17.5	20.3
1/2	5.7	9.7	9.0
2	6.7	10.7	9.0
4	14.5	21.2	17.0
10	27.2	32.7	27.2
100	59.5	58.8	—

By comparison of Table VI with Tables I and II, it will be seen that the agreement is very satisfactory considering the fact that Fletcher's values were obtained by an entirely different experimental method. Since it appears very reasonable to assume that judgments of fractional loudness are made upon the basis of nerve discharges per unit time, this work may be considered as verification of the validity of Fletcher's scale as a measure of sensation.

The rough determination of the 1000 cycle threshold made during these tests gave the average threshold of the observers used as about five decibels above 0.00053 bar. Part, at least, of this difference might be due to the fact that the threshold readings were taken quite hurriedly. However, if this measured value of the threshold is taken as a basis, the loudness of the test tones would be 25, 50 and 75 decibels. By using these values, the results as computed from Fletcher's data are those shown in Table VII. These values agree even better with the observed values than do those of Table VI.

TABLE VII. *Changes in sensation level computed from Fletcher's G function, taking loudness levels of test tones from measured threshold.*

	25 db	50 db	75 db
1/100	22.5	37.8	54.0
1/10	13.3	24.0	33.2
1/4	8.7	15.8	21.0
1/2	4.8	8.4	11.0
2	6.0	10.5	8.7
4	12.8	21.5	17.2
10	23.6	33.7	27.6
100	57.2	60.3	—

[4] R. R. Riesz, Phys. Rev. **31**, 867 (1928).

[5] From data presented at a meeting of the American Standards Association Subcommittee on Noise Measurement. Dr. Fletcher has informed the writers that these data will be published soon.

Conclusions

The results of this work may be briefly summarized as follows:

(1) A given fractional change in loudness as judged by the ear corresponds to different energy changes for sounds of different intensity. Numerical values are given in the curves of Fig. 1.

(2) A given fractional change as judged by the ear corresponds to different energy changes for sounds of different frequency. For this reason it is necessary, in applying Fig. 1, to use equivalent 1000 cycle loudness values, or to make use of equal loudness contours, such as those of Kingsbury.[3] A fractional change in loudness can not be stated in terms of sensation level only.

(3) An individual's judgment of fractional loudness is easily and greatly influenced by the conditions of the test.

(4) The average of the individual deviations upon repeating the test was greater than the mean deviation from the mean.

(5) The ratio of intensities corresponding to a fractional loudness was different than the corresponding ratio obtained from multiple loudness judgments.

(6) To the majority of observers, fractional or multiple loudness values have as much meaning as does the equality in loudness between sounds of different complexity or frequency.

(7) The data obtained agree very well with Fletcher's data showing the number of nerve impulses per second. Thus it appears that loudness judgments are made upon the basis of actual sensation.

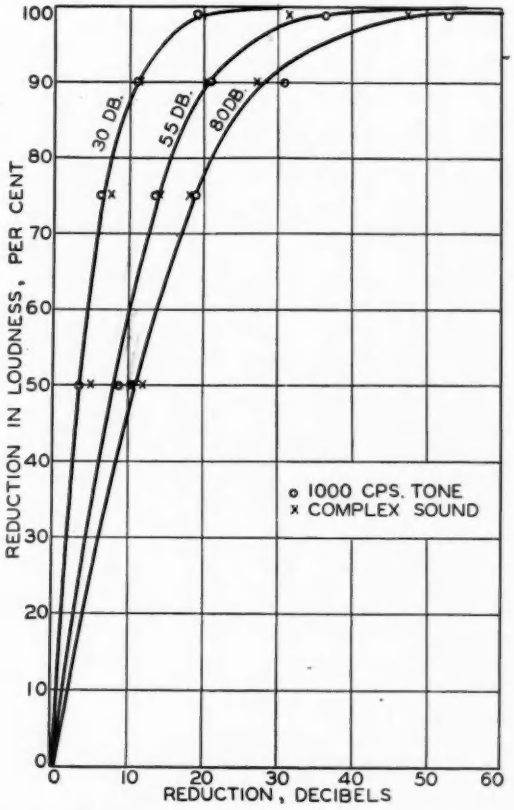

Fig. 1. Changes in sensation level corresponding to fractional loudness reduction.

Two Integral Laws of Sound Perception Relating Loudness and Apparent Duration of Sound Impulses

SAMUEL LIFSHITZ,* *Architectural Construction Institute of Moscow*

(Received June 1, 1933)

IN order to explain the dependence of the optimum reverberation time, for music, upon the volume of the room, the following postulate was proposed in 1925:[1] The value of $t \log I$ which we have called the energy of musical perception must have the same constant value for all closed spaces; where I is the sound intensity expressed in terms of the threshold of audibility; $\log I$ corresponds to the loudness and t is the real reverberation time of the room.

Since the reverberation is a continuation of the sound impulse after the source has ceased, the postulate can be represented in the following form:

$$\int_{t_1}^{t_2} \log I dt = \text{const.} \qquad (1)$$

This means, according to MacNair[2] that our ear is a ballistic instrument which integrates the loudness throughout the time. The scientific discussion and the experimental investigations which followed our published work show that while this statement of the problem excites the doubt of certain authors (Schuster, Waetzmann[3] and Knudsen[4]) the conclusions which result from it coincide surprisingly well with the experimental data obtained in different countries during the last eight years. This fact makes it appear reasonable that the above postulate is based upon fact. The purpose of the present paper is to discuss the validity of this postulate. For this purpose we have employed apparatus as shown in Fig. 1.

A cylinder C of insulating material rotates with a constant speed whose value can be adjusted at will. This cylinder has on its surface a number of series of conductive contacts arranged in the form of rings. These contacts are equally spaced in the various rings. A travelling electrode K can slide along the surface of the drum to engage any of the contact groups. When this electrode touches one of the contacts, it closes the circuit of the telephone T_1 through the supply battery B. The second telephone T_2 is connected to an audiometer graduated in two db steps.[5] Each contact gives the telephone T_1 two sound impulses or clicks, namely one on closing and one on opening the circuit.

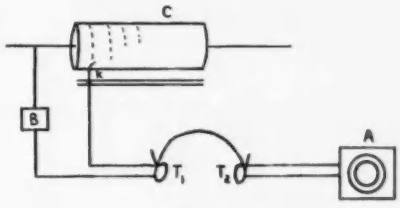

FIG. 1.

By displacing the electrode K along the axis of the cylinder to another group of contacts, it is possible to make the total impulse in the telephone T_1 come from two, three, etc., contacts. By means of the telephone T_2 and the audiometer, the apparent loudness of the total impulse obtained from any number N of the contacts can be determined for each case.

Preliminary results have already shown that the total impulse seems to be not only longer but also louder, the larger the number of contacts from which this impulse is taken. The results of measurements made with the audiometer are given in Table I. The average differences correspond to the logarithms of the ratios of the number of contacts; i.e., log 4 : log 2 : log 8, respectively.

Table II shows similar data where the cylinder was rotated at a speed to give 232 contacts

* Edited by J. P. Maxfield.

[1] Lifshitz, Phys. Rev. **25**, 391 (1925) and **27**, 618 (1926); J. Acous. Soc. Am. **IV**, 112 (1932).

[2] MacNair, J. Acous. Soc. Am. **I**, 242 (1930).

[3] Schuster and Waetzmann, Ann. d. Physik **1**, 671 (1929).

[4] V. Knudsen, J. Acous. Soc. Am., **II**, 434 (1931).

[5] As it is used in America and in the U.S.S.R.

TABLE I. *Loudness in db for the various number of contacts.*

Cycle—116 Contacts per second.

Number of contacts	1	4	8	Difference in db 1–4	4–8	1–8
Audiometer readings (db)	70	76	78	6	2	8
	66	71	74	5	3	8
	48	55	58	7	3	10
	46	52	58	6	6	12
	36	42	46	6	4	10
	30	35	36	5	1	6
Average				6	3	9

TABLE II.

Cycle—232 Contacts per second.

Number of contacts	1	4	8	Difference in db 1–4	4–8	1–8
Audiometer readings (db)	73	78	82	5	4	9
	62	68	72	6	3	9
	58	64	67	6	3	9
	48	54	57	6	3	9
	41	46	49	5	3	8
	34	40	43	6	3	9
Average				5.7	3	9

TABLE III.

Cycle—463 Contacts per second.

Number of contacts	1	4	8	16	Difference in db 1–4	4–8	8–16	4–16	1–16
Audiometer readings (db)	68	72	76	76	6	4	6	4	10
	66	70	74	76	4	4	2	6	10
	60	66	68	72	6	2	4	6	12
	52	58	62	66	6	4	4	8	14
	46	52	56	58	6	4	2	6	12
	34	42	44	48	8	2	4	6	14
Average					6	3.3	2.7	6	12

per second. In this case also the ratio of the differences corresponds satisfactorily to the ratio: log 4 : log 2 : log 8.

Table III shows further data of the same character with 463 contacts per second in contact groups of 1, 4, 8 and 16, respectively. In this case the ratio of the differences satisfactorily corresponds to ratio: log 4 : log 2 : log 2 : log 4 : log 16 as would be expected from the postulate.

From these results we may conclude that our ear is a ballistic instrument which integrates the single impulses. The total loudness would be represented, therefore, by the equation

$$L = \log (IN), \tag{2}$$

where the N is the number of single impulses. If I represents the continuous function, we shall have for the loudness the following expression:

$$L = \log \int_{t_1}^{t_2} I dt. \tag{3}$$

Our ear is really a ballistic instrument, but a purely physical one as it integrates the intensities and not the loudnesses as has been mentioned by MacNair. This law holds between definite limits. First the ear ceases to integrate impulses when they become so widely separated that they can be clearly distinguished from one another. On the other hand, the other limit is approached when the impulse becomes so long that it partakes of the nature of a sustained tone. The aim of the further work to be discussed here is to establish these limits. By simple calculation, it can be shown that the above loudness integral which we have obtained cannot explain the optimum reverberation time. Consequently, there must exist some other form in which the facts can be expressed. Further investigations were made with similar apparatus but changed to correspond to that shown in Fig. 2. Instead

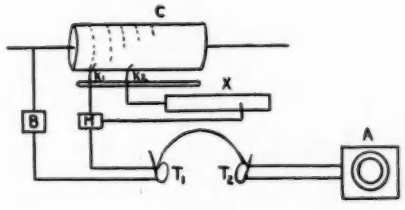

FIG. 2.

of the single electrode K, we have now two electrodes K_1 and K_2, each sliding independently along the axis of the cylinder to pick up any desired group of contacts. The rheostat X of very high resistance is inserted in the circuit of electrode K_2. By means of the switch M, one may obtain the impulse, for comparison, in the same telephone T_1 successively from contacts K_1 and K_2. By means of the audiometer A, we may measure as before the loudness of the impulses obtained from K_1 and K_2. The data

so obtained permit us to make the following statement: The seeming duration of the impulse varies with the loudness and does not coincide always with its real duration. If the number of the contacts controlling K_1 and K_2 are different (e.g., 3 and 8), the first impulse will naturally seem shorter if they are both of the same loudness; but if by increasing the resistance X we decrease the loudness of the impulse from K_2, the latter will seem shorter and we shall reach a condition where the two impulses appear of equal duration. If we continue to increase the resistance X and consequently to decrease the loudness of the impulse K_2, this latter can be made to appear of even shorter duration than K_1.

By means of direct measurements, we have determined the loudnesses for which sound impulses of different actual durations appear to have equal durations. The results are shown in Table IV.

TABLE IV.

Cycle—80 Contacts per second.

No. of contacts	Duration of the impulse	Loudness in db	Average	Ratio
3	0.0375 Sec.	68 64 78 78 78	77	3
8	0.1000 "	27 30 27 30 30	29	8
3	0.0375 "	78 78 78 75 78	77	3
6	0.0750 "	42 42 36 39 42	40	5.8
3	0.0375 "	78 78 78 78 78	78	3
5	0.0625 "	54 42 42 48 48	47	5
3	0.0375 "	78 78 78 78 78	78	3
4	0.0500 "	66 60 60 63 63	63	3.7

The results show that the ratio of loudness is as follows:

$$3 : 3.7 : 5 : 5.8 : 8.$$

This checks rather well with the ratio of the number of contacts, namely,

$$3 : 4 : 5 : 6 : 8.$$

Thus the apparent duration of the impulse D is determined by the expression—

$$D = \log (IN) \tag{4}$$

and in the case where I is a continuous function—

$$D = \int_{t_1}^{t_2} \log Idt. \tag{5}$$

This integral completely explains the dependence of the optimum reverberation time upon the volume of the room. It corresponds to what we previously called energy of musical perception and signifies apparent duration rather than energy. On the basis of this integral of duration, we can obtain a simple explanation for the optimum reverberation time, namely, for the artistic musical performance, it is necessary that the apparent duration of the tone shall have the same fixed value under all conditions.

CONCLUSIONS

(1) Our ear is a ballistic instrument which integrates the sound intensity throughout a definite time interval. The loudness of the definite impulse is determined by the following integral:

$$\log \int_{t_1}^{t_2} Idt.$$

(2) The apparent duration of the definite sound impulse depends upon its loudness and is determined by the apparent duration integral:

$$\int_{t_1}^{t_2} \log Idt.$$

(3) The dependence of the musical optimum reverberation time upon the volume of the room can be calculated by equating the duration integral to a determined value. This relationship means that for artistic musical performance, it is necessary that the apparent duration of the tone depending upon the reverberation time shall be equal under all conditions to a fixed value.

Measurement of Transmission Loss Through Partition Walls

E. H. BEDELL AND K. D. SWARTZEL, JR., *Bell Telephone Laboratories*

(Received May 10, 1933)

This paper reviews the theory and describes the method used at Bell Telephone Laboratories of measuring the transmission loss through partition walls. The partition to be tested is built into an opening between two adjacent but structurally isolated rooms. A loud speaker acts as a source of sound in one room and a portion of the sound energy is transmitted into the second room through the test partition. The transmission loss is taken as

$$TL = L_1 - L_2 - 0 \log_{10} (a_2/A),$$

where L_1 and L_2 are the intensity levels in the source and test room respectively, expressed in db, a_2 is the absorption in the test room and A is the area of the partition. The levels L_1 and L_2 are measured and plotted with a moving coil microphone and an automatic level recorder, and a beat frequency oscillator is used as a source of tone so that the frequency may be varied continuously. Measurements with a continuous variation in frequency enable resonances in the partition to be much more easily and quickly detected than is possible when measurements are made at discrete frequency intervals. Both pure and frequency modulated tones have been used for the measurements. Results of measurements on a few partitions are given.

DURING the past few years measurements of sound transmission through various types of partition walls have been made at Bell Telephone Laboratories. It is the purpose of this paper to outline the theory and describe the method used for these measurements.

The theory of the method is not new but will be reviewed briefly. Let the wall structure to be tested be built into an opening between two adjacent but structurally isolated rooms, in one of which, the source room, a source of sound is placed, and into the second of which, the test room, sound is transmitted by the test partition. The average sound energy density, ρ_1, established by the source in the source room will be[1]

$$\rho_1 = 4E_1/a_1c, \tag{1}$$

where E_1 is the rate at which the source supplies energy to the room, a_1 is the total absorption in the source room, and c is the velocity of sound. Buckingham has shown[2] that the rate, ϵ, at which sound will strike the test panel is

$$\epsilon = \rho_1 cA/4 \tag{2}$$

where A is the area of the panel. Then if T is the percentage transmission, or transmittivity, of the panel, the rate E_2, at which energy will be supplied to the test room is[3]

$$E_2 = T\epsilon = (T\rho_1 cA)/4 \tag{3}$$

and this supply of energy will build up an energy density, ρ_2, in the test room such that

$$\rho_2 = (T\rho_1 A)/a_2, \tag{4}$$

where a_2 is the total absorption in the test room. Then

$$T = (\rho_2/\rho_1)(a_2/A). \tag{5}$$

Since the ratio of transmitted to incident energy is very small for most panels, the transmission loss gives a more useful comparison of the insulation value of various walls. Transmission loss[4] in decibels is defined as

$$TL = 10 \log_{10} (1/T). \tag{6}$$

From (5) and (6)

$$TL = L_1 - L_2 - 10 \log_{10} (a_2/A), \tag{7}$$

where L_1 and L_2 are the energy density levels in the source and test room, respectively, expressed in db.

As Buckingham points out, Eq. (5) or Eq. (7) offers probably the simplest method of measuring

[1] Crandall, *Theory of Vibrating Systems and Sound*, p. 282.

[2] Bur. Stand. Sci. Paper No. 506, May (1925).

[3] The usual assumption is made that no energy enters the test room from the source room other than that transmitted by the panel.

[4] Knudsen, J. Acous. Soc. Am. II, 129 (1930).

the transmittivity of a panel, provided a satisfactory method of measuring L_1 and L_2 is available. It is primarily in the method and apparatus used for measuring these energy density levels that the method of measuring transmission loss here presented differs from those previously used.

In Fig. 1 is shown the plan of the laboratory used for making transmission loss measurements.

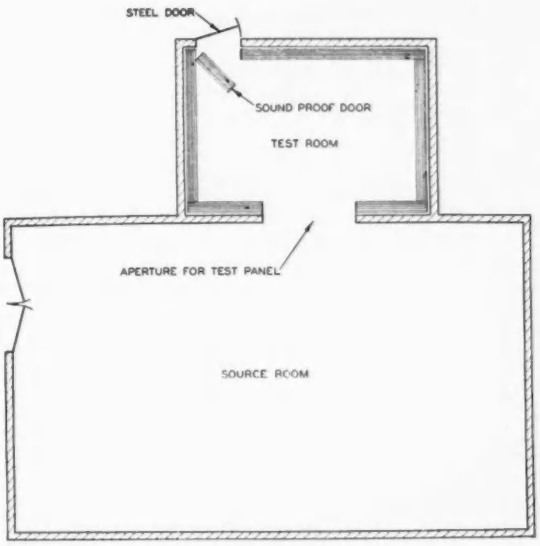

FIG. 1.

The source room, which is also used as a reverberation chamber for absorption measurements, has a volume of approximately 9500 cubic feet. The walls are of 6-inch solid masonry with an opening 6 feet × 6 feet into the test room. The opening is near the center of one wall of the test room, which has a volume of approximately 1750 cubic feet and which also has 6-inch solid masonry walls. In addition, the test room has a 3-inch inner shell of celotex and sheet metal on wood studs, which is flexibly supported from the concrete floor at four points. The inner shell is separated from the masonry walls by a 4-inch air space and this air space is closed with hair felt and soft rubber around the 6-foot × 6-foot opening. The test room has a reverberation time of 0.4 second, approximately constant with frequency, and a corresponding total absorption of 180 square feet. The absorption in the test room is but little influenced by the panel under test therefore, so that the term a_2/A in Eq. (7) need not ordinarily be redetermined for each panel tested.

A schematic diagram of the apparatus used is given in Fig. 2. The oscillator is of the heterodyne type and has a nearly constant output

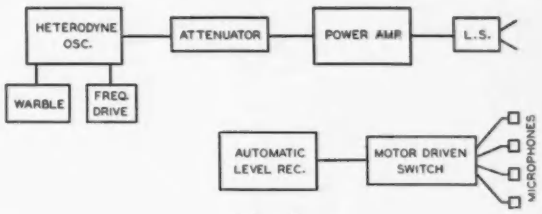

FIG. 2.

over the frequency range from 20 to 10,000 cycles per second. It is equipped with a motor-driven modulating condenser by means of which frequency modulated, or warble, tones covering a band up to 100 cycles per second may be obtained, the warble frequency being adjustable up to 10 cycles per second. A second motor is provided on the oscillator so that the frequency may be varied continuously at any desired rate. A power amplifier and loudspeaker capable of delivering considerable amounts of power without distortion are used, so that a sufficiently high intensity for satisfactory measurement in the test room is obtainable. The microphones used are of the moving coil type described by Wente and Thuras.[5] The motor-driven rotating switch may be used to connect in sequence a number of microphones to the level recorder. It is provided so that the average response of a number of microphones at different points in the room may be taken on a single curve. The automatic level recorder is a machine which plots continuously, on a moving paper chart, a curve whose ordinate is proportional to the logarithm of the electrical input furnished to it. As the frequency of the oscillator is varied slowly through the range for which transmission data are desired, the level recorder is used to plot the response of the microphones in the rooms.

We find that the continuous record so obtained has several definite advantages over the point to point readings of an indicating instrument. The records are permanent and are much more easily and quickly obtained: most of the records

[5] Wente and Thuras, J. Acous. Soc. Am. III, 44 (1931).

are taken with the oscillator driving motor geared so that the frequency is changed, approximately logarithmically, from 20 to 10,000 cycles per second in five minutes. The continuous curves make it possible to locate any resonances in the transmission of a panel without the necessity for a large number of measurements at discrete fixed frequencies.

Since the theory is based on measurements of the mean energy density throughout the volume of the two rooms, it is necessary to obtain a space average as well as to eliminate possible errors due to the standing wave system. In the source room the reverberation time is approximately 8 seconds so that, neglecting interference, a very nearly uniform distribution of energy is obtained at all distances greater than a few feet from the source. The test room, however, is quite "dead" and the distribution therefore not uniform.

The portions of curves shown in Figs. 3 to 5, all taken in the source room, illustrate methods of obtaining a space average and of eliminating the effects of the interference pattern. The curves in Fig. 3 were taken with a single microphone, without a warble, but at different operating speeds on the level recorder. Curve 1 was plotted with the rate of response of the level

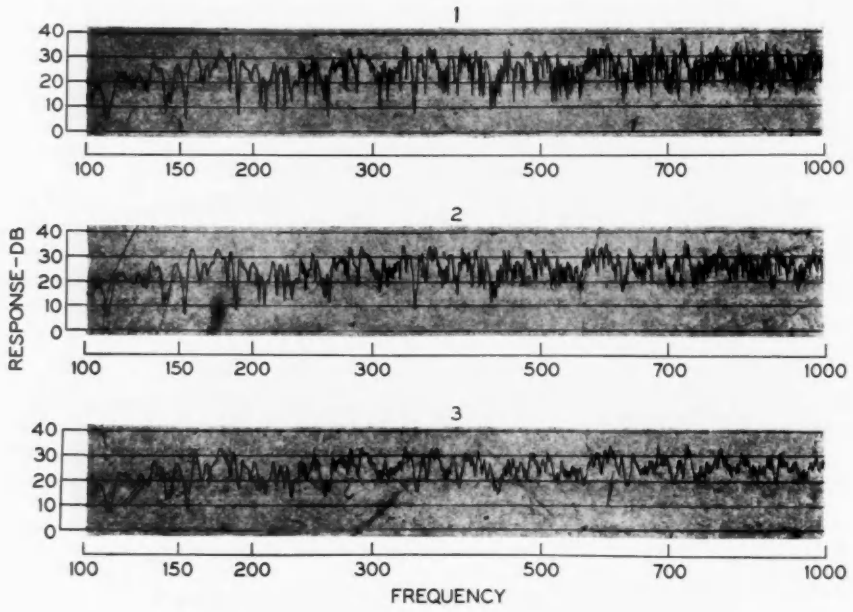

FIG. 3.

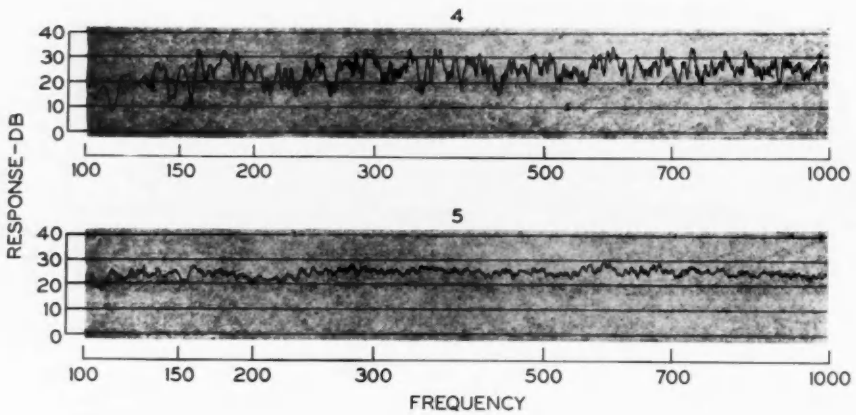

FIG. 4.

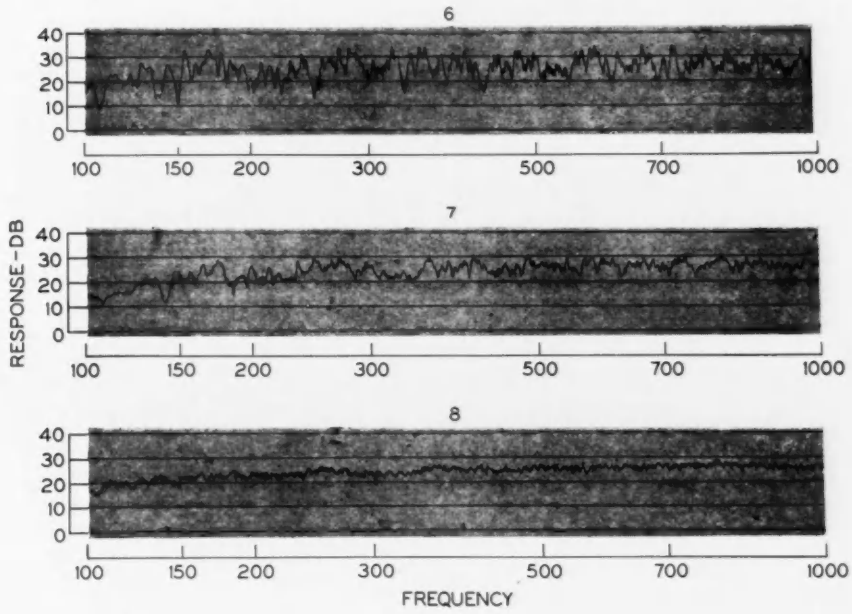

FIG. 5.

recorder adjusted to 120 db per second. Curve 2 was taken at 60 db per second, and curve 3 at 30 db per second. The rapid variations in these curves are all due to the shifting of the interference pattern as the frequency is varied. It is evident from these curves that before an accurate measurement of the energy density can be made, some method of either eliminating the standing wave system itself or of averaging out its effects must be adopted.

Curve 4 in Fig. 4 is a repetition of curve 3 of Fig. 3, and curve 5 differs only in that a warble tone having a band 100 cycles wide, with the modulating condenser driven at 8 revolutions per second, was used. These curves show that such a warble tone is not sufficient to eliminate the effects of interference. However, with a continuous curve of microphone response, such as curve 5, it is possible to obtain graphically an average value of the intensity for any frequency interval.

Curve 6 in Fig. 5 is again a repetition of curve 3. Curve 7 was taken using the motor driven switch and three microphones, the switch being driven at such a speed that the microphones were alternately connected to the level recorder for a period of approximately 0.013 second. This curve shows a smoothing out of the response somewhat less than that obtained when using the warble tone, but again an average value of microphone response can be obtained graphically. Curve 8 was taken when both the warble tone and the motor-driven switch with three microphones were used. Here the effects of interference are almost completely eliminated, and the intensity may be determined within narrow limits.

Results of transmission loss measurements on a few partitions are given in Figs. 6 and 7. Curve 1 of Fig. 6 shows the transmission loss as a function of frequency for a 6-foot × 6-foot metal frame door having four 28-inch × 28-inch panels of $\frac{1}{4}$-inch plate glass. This door was loosely clamped at the edges against a felt strip about $\frac{1}{2}$ inch in thickness so that some of the transmitted sound may have been due to the

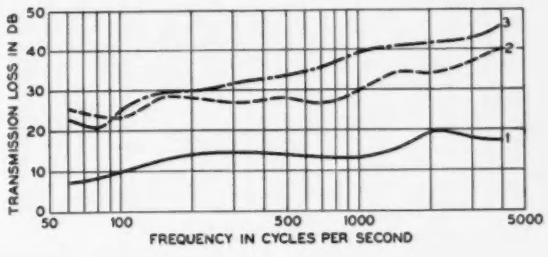

FIG. 6.

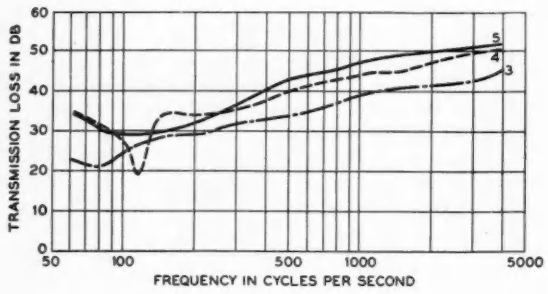

FIG. 7.

rather imperfect seal. Curve 2 shows the transmission loss for a standard unplastered 3-inch hollow gypsum tile wall, and curve 3 is for the same wall with two coats of gypsum plaster, each about $\frac{1}{2}$ inch thick, on each side.

In Fig. 7 curve 3 is again for the plastered 3-inch hollow gypsum tile wall, and curve 4 is for the same wall, with a second wall of 1-inch plaster on expanded metal lath and light metal channel studs, flexibly supported from the plastered gypsum tile wall. The added wall with its supports was resonant in the region of 115 cycles per second and this resonance shows up as a dip in the transmission loss curve. When the flexible supports were changed so as to give additional damping, the transmission loss characteristic given by curve 5 was obtained.

No attempt is made to express the insulation value of a wall with a single figure, as no generally acceptable method of weighting the various frequencies or frequency intervals is available.

A New Portable Meter for Noise Measurement and Analysis.*

W. O. Osbon and K. A. Oplinger, *Westinghouse Electric and Manufacturing Company*

(Received May 10, 1933)

This paper describes (1) a portable noise meter, the development of which is based upon several years experience in the field of industrial noise measurements, (2) a new superheterodyne analyzer attachment for the noise meter which permits analysis of noises with a high degree of selectivity and (3) a moving coil type of pick-up for making vibration measurements. The principle considerations in the design of the various units have been ruggedness, simplicity of operation, portability, and accuracy. A general discussion of the factors involved in the design and use of noise measuring instruments is given.

Introduction

THE history of the development of any particular machine is a description of the analysis and solution of a succession of important problems. At one time or another, either dependability, cost, efficiency, size or weight, or appearance have been of first importance. At the present time, for certain kinds of machinery at least, more attention is being focussed upon the problem of reducing noise than upon any other, and the rapidly increasing "noise-conciousness" of the public is causing nearly all machinery manufacturers to place greater and greater importance upon the noise problem.

Although no standards of allowable noise have yet been formulated, there is an increasing tendency, at least among buyers of electrical equipment, to include noise clauses in their specifications. The organization with which the authors of this paper are connected has for several years recognized this tendency, and consequently has devoted considerable attention to the problem of reducing noise produced by electrical machinery.†

In order to facilitate investigations of machinery noise, this organization, a number of years ago, began to develop methods and apparatus for its measurement. Early work in this direction culminated in the development of a tuned circuit type of analyzer, described by Messrs. Spooner and Foltz before the American Institute of Electrical Engineers early in 1929.[1] In spite of several important limitations inherent in analyzers of this type, this instrument has been used until recently to great advantage in many noise investigations. Two years later, in 1931, K. A. Oplinger, one of the authors of this paper, developed a total noise meter[2] which proved very useful for evaluating or comparing the intensities and loudnesses of various sounds.

Since 1931 several improvements have been made in the total noise meter, and a new type of analyzer, in the form of an attachment for the noise meter, has been developed. The purpose of this paper is to describe the complete noise measuring equipment in its present form.

General Description

The principal considerations in the design and construction of the various elements of the noise measuring and analyzing equipment have been ruggedness, simplicity of operation, portability, and accuracy. All vacuum tubes are of a rugged, nonmicrophonic type, and are operated so as to insure long life and constancy of characteristics.

The apparatus, arranged for a typical noise test, is illustrated in Fig. 1. The sound pick-up, shown mounted on its tripod, is a standard high-quality condenser microphone of the type used extensively in broadcasting and sound recording. Three stages of amplification are included in the microphone housing. When the microphone is not in use it is carried in the case shown at the left. This case also contains space for the microphone batteries, the tripod, cables, and other accessories. Thus the microphone with

* Scientific Paper No. 661.

† See references 1, 4, 10, 11 in bibliography.

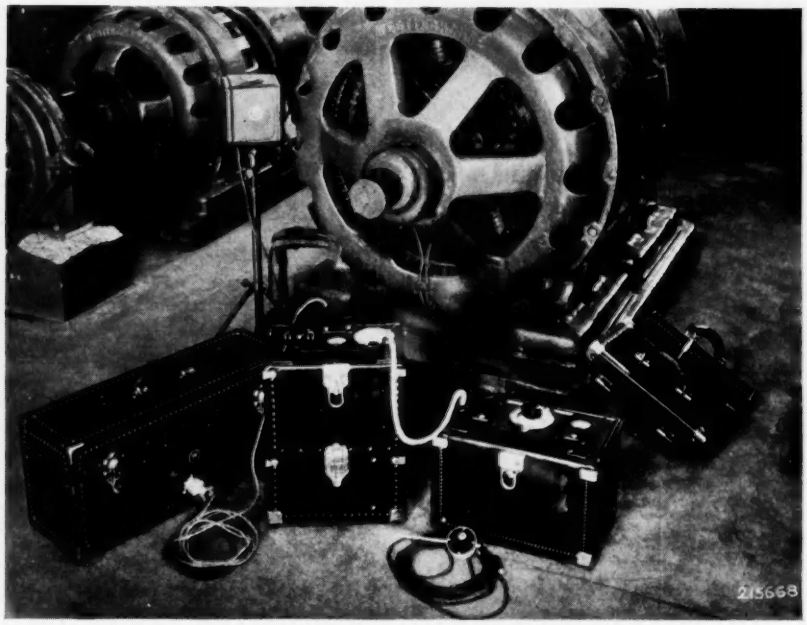

FIG. 1. Complete equipment in a typical noise test set-up.

its case is a completely self-contained and separate unit.

The noise meter amplifier, the central unit in Fig. 1, is also completely self-contained, batteries for its power supply being carried in the lower compartment of the amplifier case. Power for the analyzer attachment, shown at the right, is obtained from the same set of batteries. A vibration pick-up, used in place of the microphone when vibration instead of noise is to be measured, is on the floor in front of the analyzer. These units are described in detail in the following paragraphs.

NOISE METER AMPLIFIER

The noise meter amplifier, Fig. 2, is a high quality, three-stage, transformer coupled amplifier with a calibrated attenuator in the input circuit and a calibrated meter to measure the output. The attenuator is logarithmic, each step increasing the amplification by 2 to 1, or by 6 decibels. The output meter is of the rectox type and has both pressure and decibel scales, so that observations can be expressed in either dynes per sq. cm or decibels, without the necessity of converting from one unit to the other. The output meter deflection is proportional to the square of the input, making the readings independent of wave shape.

FIG. 2. Noise meter amplifier.

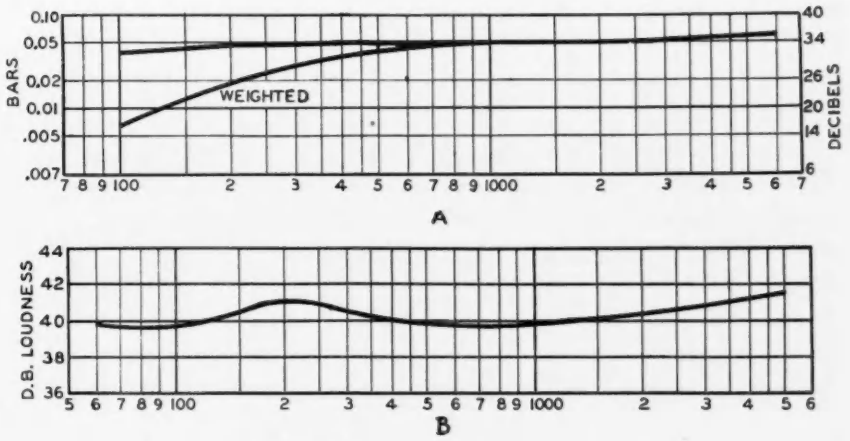

FIG. 3. A, response of noise meter to pressure of 0.05 bar. B, weighted response of noise meter to tones of 40 decibel loudness.

The lowest sound pressure (at the microphone diaphragm) that will produce an easily readable deflection of the output meter is 0.01 dyne per sq. cm and the maximum pressure that can be observed is 102 dynes per sq. cm. These pressure limits correspond, respectively, to 20 db and 100 db above the reference level of 0.001 dyne per sq. cm. Thus the range of the instrument is approximately 10,000 to 1 in pressure, or 80 db.

For making loudness measurements there is provided a frequency-weighting network which gives the instrument a response characteristic corresponding to the Kingsbury equal loudness contour[3] passing through a point 40 db above 0.001 dyne per sq. cm at 1000 cycles. Fig. 3A gives the weighted and unweighted frequency response curves of the noise meter and Fig. 3B shows its response to pure tones of 40 db equivalent loudness.

A receptacle plug in the right front corner accommodates the cable to the analyzer, and the large toggle switch at the left changes the equipment from a total noise meter to an analyzer. An output jack enables the unit to be used as a high quality, general purpose amplifier.

ANALYZER ATTACHMENT

General

The principal objection to the tuned circuit analyzer mentioned above is the fact that its selectivity is poor at high frequencies. The desirable analyzer is one in which the selectivity is very sharp and remains constant throughout the entire range of audiofrequencies. A mechanical filter is the only type of selective device

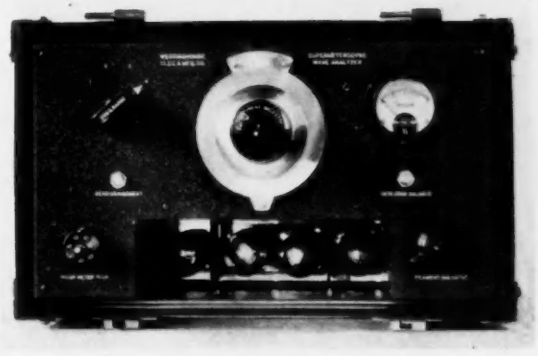

FIG. 4. Top view of analyzer attachment.

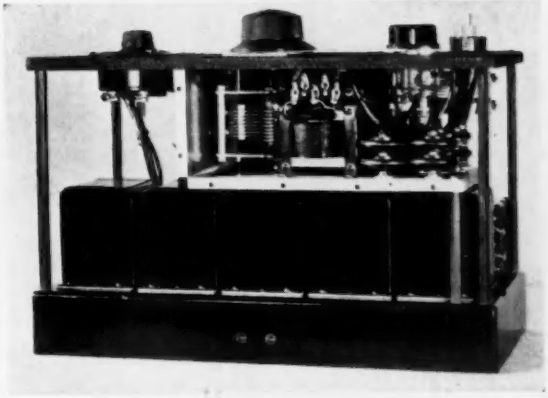

FIG. 5. Rear view of analyzer attachment with tuning compartment shield removed.

which can be made sharp enough for noise analysis at high frequencies. A mechanical filter, however, cannot be conveniently tuned to various frequencies in the audiorange as can a tuned electrical circuit. It is necessary, therefore, to resort to the superheterodyne principle for converting the component frequencies of a noise wave to the fixed filter frequency.*

Figs. 4 and 5 show two views of the superheterodyne analyzer attachment described below. The mechanical filter is mounted in the base. The audiorange covered by the analyzer is from 30 c.p.s. (a limit determined by the quality of the audiotransformers) to 5200 c.p.s. There is less than 2 db variation in the frequency-response characteristic between these limits.

The superheterodyne principle

The superheterodyne principle, as it is applied to the noise analyzer, can be best described by referring to the block diagram of the equipment, Fig. 6. The wave to be analyzed is picked up by the sound or vibration pick-up, attenuated to a suitable level, and amplified. Then, instead of passing directly to the output meter, as when measuring total noise, it is applied to the input circuit of a vacuum-tube detector. At this point there is superposed upon it the signal from an oscillator, the frequency of which is variable between about 6800 and 12,000 c.p.s. For any particular setting of this oscillator frequency, the detector output will contain frequencies equal to the differences between the oscillator frequency and each of the component frequencies of the noise wave.† When one of these difference frequencies equals the resonant frequency of the mechanical filter (approximately 6800 c.p.s.), it will be passed by the filter, through the following stages of amplification, to the output meter on the noise meter amplifier. From the meter reading and the attenuator setting the amplitude of the noise component producing this difference frequency can be determined and its frequency obtained from the setting of the

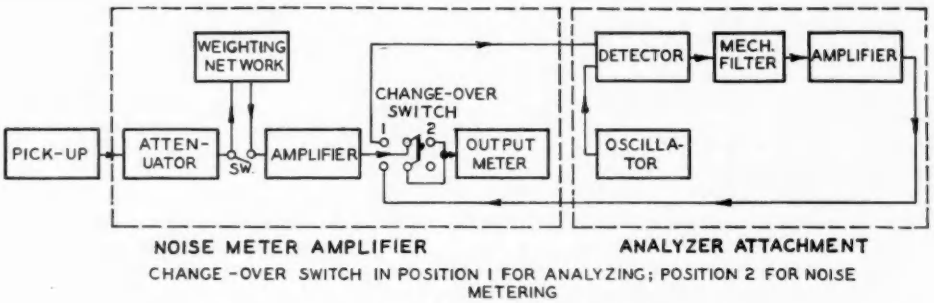

FIG. 6. Block diagram of noise metering and analyzing equipment.

oscillator tuning condenser dial. Thus, in order to analyze any complex wave it is only necessary to vary the oscillator frequency until the difference between it and each of the component frequencies in turn equals the frequency to which the mechanical filter is selective.

Detector circuit

By using a power detector and by keeping the noise-input small compared to the oscillator input, it is possible to eliminate spurious readings due to undesirable frequency components in the detector output current. The relatively large component due to the oscillator is reduced to a minimum by means of the familiar balanced circuit for carrier suppression shown in Fig. 7. This balanced arrangement is especially useful in preventing excessive output meter deflections when the oscillator frequency approaches the mechanical filter frequency. Differences in the phase angles of the two halves of this circuit are corrected by factory adjustment of the detector output transformer resistors, and differences in

* An electric wave analyzer utilizing the heterodyne principle has been developed by C. R. Moore and A. S. Curtis. For a description of this apparatus see reference 9.

† The detector output will contain various frequencies in addition to the difference frequencies, but the latter are the only useful components. For an analysis of the detector action see reference 9 in the bibliography.

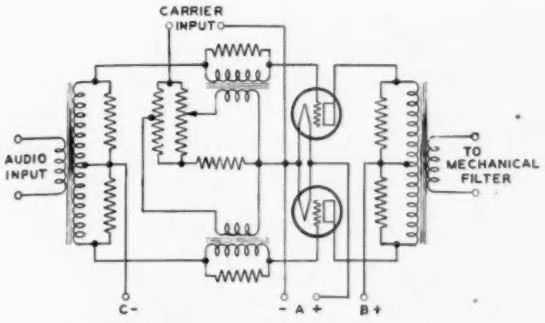

FIG. 7. Schematic diagram of detector.

amplitude are taken care of by means of the potentiometer in the detector input circuit. With this arrangement it is possible to obtain a very high degree of balance.

Oscillator

Obviously the most important requisite of the oscillator is frequency stability. With the circuit shown in Fig. 8 the variations in oscillator frequency due to changes in battery voltages are reduced to a minimum. As seen in Fig. 9 the maximum deviation from 7000 c.p.s., due to reasonable variations in the battery voltages, is 6 cycles; but since adjustments are provided to compensate for voltage variations, the frequency error is ordinarily considerably less than this. At the higher values of the oscillator frequency, corresponding to the higher audiofrequencies, the maximum frequency deviation is of the order of two or three times that shown in Fig. 9.

The oscillator range is divided into four bands to give an open frequency scale, and a small vernier condenser permits adjustment of the oscillator frequency to the filter frequency for correcting the zero setting of the tuning dial. To prevent off-scale deflections of the output meter when making this and the detector balance adjustments, the amplifier sensitivity is automatically reduced by a system of contacts shown in Fig. 8. These contacts are closed by the main tuning condenser and the range selector switch when the oscillator frequency nears a value corresponding to zero audiofrequency.

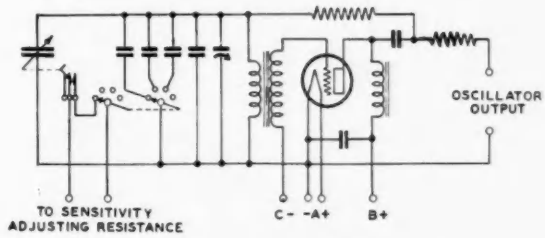

FIG. 8. Schematic diagram of oscillator.

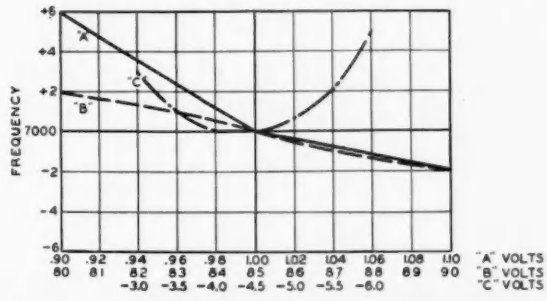

FIG. 9. Variation of oscillator frequency with battery volts.

Mechanical filter

The mechanical filter, illustrated in Fig. 10, is of an unusual design. It is extremely rugged and permanent in its characteristics. The filter consists of a brass rod supported at the center in such a manner that it will respond to longitudinal vibrations of a wave-length corresponding to twice the length of the rod. Attached to each end of the rod is a small coil that floats in a steady magnetic field. The detector output is applied to one of these coils, so that when the detector current contains a component of resonant frequency, a vigorous longitudinal vibration will be set up in the rod. The voltage generated in the other coil due to this vibrational velocity is then amplified and measured by the output meter.

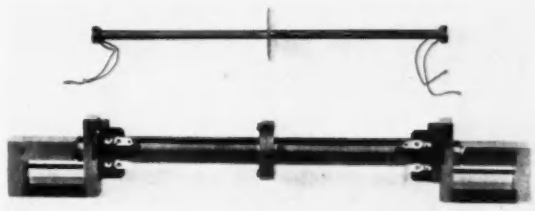

FIG. 10. The mechanical filter. (Above) the filter unit. (Below) the complete assembly.

The central support of the rod is in the form of a flexible diaphragm, so that if there is any unbalance between the two halves of the filter, the compliance of the support will allow the rod to seek its own natural nodal point. Since the natural frequency of the filter is quite high, the

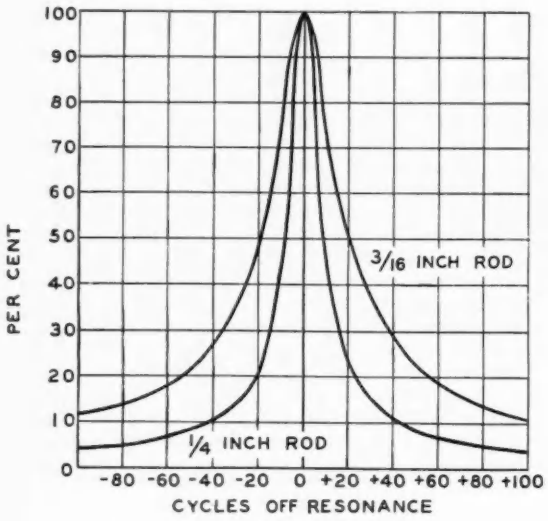

FIG. 11. Selectivity of analyzer.

diaphragm need not be so flexible as to cause a lack of rigidity in the structure. The effect of extraneous modes of vibration is eliminated by clamping the diaphragm between layers of soft rubber and by a tuned transformer in the amplifier following the filter.

It is evident from Fig. 11 that the selectivity of the filter is a function of the diameter of the filter rod. The $\frac{1}{4}$-inch diameter rod has been found satisfactory for noise analyses. For electrical wave analyses where there is no frequency variation, greater selectivity is sometimes desirable. In such cases a $\frac{5}{16}$-inch filter rod is used.

The vibration pick-up

The vibration pick-up, Fig. 12, is substituted for the microphone when the vibration of a surface is to be measured or analyzed. The pick-up is of the moving-coil type and in operation is similar to a seismometer. The coil is securely attached to the relatively light frame, and the field structure is supported within the frame by two very flexible leaf springs which restrict its motion to a direction parallel to the coil axis. When the stylus is pressed against a vibrating surface, the frame and coil will follow the motions of the surface and the magnet structure will remain stationary in space for all frequencies above the resonant frequency of the system. Resonance occurs at about 30 c.p.s. and excessive motion of the field at this frequency is prevented by two small felt dampers.

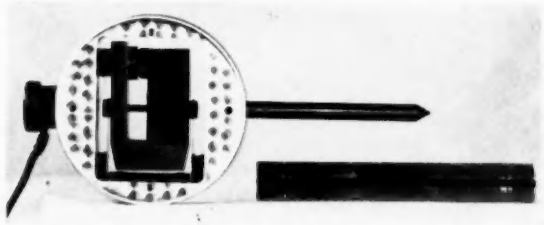

FIG. 12. The vibration pick-up with side covers removed.

The voltage generated in the pick-up coil due to its motion relative to the magnetic field is proportional to the vibrational velocity of the vibrating surface. This quantity more nearly corresponds to the sound pressure radiated by the surface than any other measure of the vibration.

Occasionally it is important to know the modes of vibration of a vibrating surface. For example, in studying the vibration of the stator of a rotating machine, the distortion of the surface can be deduced if the phase angles between the velocities at some reference point and at various other points on the surface are known. It is very easy to obtain such data by the use of two equally sensitive vibration pick-ups connected in series so that their voltages add. The velocities at the reference point and at any one of the other points are determined separately by the application of first one pick-up and then the other. The vector sum of the two velocities is then measured by applying both pick-ups to their respective points simultaneously. This gives three sides of a triangle from which the phase angle may be determined.

If there is only one mode of vibration, the above measurements can be made by using only the noise meter amplifier and the two pick-ups. However, if there are several modes at different frequencies, it is necessary to use the analyzer and to repeat the measurements at each frequency.

GENERAL DISCUSSION OF NOISE MEASUREMENTS

It is common practice for total noise meters, when evaluating the loudness of a complex sound, to indicate a quantity which is proportional to the root mean square of the pressures of the individual components weighted according to one of the Kingsbury equal loudness contours

for pure tones. The complex sound is then said to be as loud as a 1000 cycle tone which produces the same reading on the meter.

There are two sources of error which contribute to the discrepancy between observations made in this manner and actual loudness comparisons made by ear. First, in a typical complex sound, the components are not all equally loud, and even if they were, it is not likely that the particular weighting network provided corresponds exactly to the loudness of the tones being measured. To be strictly accurate, each component of the noise wave should be weighted differently according to its own loudness. An indicating meter which could automatically perform this function would be prohibitively complicated and cumbersome. Secondly, it is known that the ear does not combine the various components of a complex sound according to the square law, and that ultimately some more complex quantity than the simple r.m.s. value will be used to express the loudness of a sound. Various interested organizations are engaged in investigations of this problem at the present time.

Thus, it is seen that the design of any practical loudness meter must be based on arbitrary premises which are a compromise between practicability and strict accuracy. In this respect the total noise meter described above conforms to the generally accepted practice.

Fortunately, however, the two sources of error mentioned above are not at all serious in what are probably the largest fields of application of loudness meters; namely, the determination of the effectiveness of corrective means for reducing the noise of machinery, rooms, etc., and for noise testing in the production line of such apparatus as motors, refrigerators, etc. In both of these cases relative values for noises of a similar character, i.e., with approximately the same pressure-frequency distribution, are measured, and the actual loudness is usually not important.

In contrast to the above, the basis of design and the use of the analyzer are perfectly straightforward. In an analysis of a noise which has discrete frequency components, the intensity of each component can be accurately determined. The results of the analysis can then be plotted on a set of equal loudness curves to determine which components are contributing most to the loudness of the noise. If the source of the noise is a rotating machine, the parts responsible for the loudest components can usually be located by correlating the component frequencies with the design constants, speed, etc., of the machine; and once these parts are found, steps can be taken to reduce their vibration.

Conclusion

The instruments which have been described are extremely simple to operate and, when used with a reasonable knowledge of their limitations, will prove to be valuable tools in the solution of any noise problem.

The authors wish to acknowledge the assistance of Mr. C. C. Horstman in the development work, and of Mr. C. R. Hanna for valuable suggestions and encouragement.

Bibliography

1. T. Spooner and J. P. Foltz, *Study of Noises in Electrical Apparatus*, Trans. A.I.E.E. **48**, 747–752 (1929).
2. K. A. Oplinger, *An Electric Ear*, Elec. J. **28**, 474–475 (1931).
3. B. A. Kingsbury, *A Direct Comparison of the Loudness of Pure Tones*, Phys. Rev. **29**, 588–600 (1927).
4. J. P. Foltz and W. F. Shirk, *Induction Regulator Noise*, Trans. A.I.E.E. **50**, 1052 (1931).
5. H. B. Marvin, *The Measurement of Machinery Noise*, Trans. A.I.E.E. **50**, 1048 (1931).
6. T. G. Castner, E. Dietze, G. T. Stanton and R. S. Tucker, *Indicating Meter for Measurement and Analysis of Noise*, Trans. A.I.E.E. **50**, 1041 (1931).
7. B. F. Bailey, *Measurement of Noise in Electrical Machinery*, Trans. A.I.E.E. **50**, 1039 (1931).
8. K. H. Pratt, *The Significance of Noise Measurements*, Elec. Eng. **51**, 705 (1932).
9. C. R. Moore and A. S. Curtis, *An Analyzer for the Voice Frequency Range*, Bell Sys. Tech. J. **6**, 217–229 (1927).
10. R. B. George, *Power Transformer Noise, Its Characteristics and Reduction*, Trans. A.I.E.E. **50**, 347 (1931).
11. Q. Graham, S. Beckwith, and F. H. Milliken, *Magnetic Noise in Synchronous Machines*, Trans. A.I.E.E. **50**, 1056 (1931).

The Determination of the Acoustical Output of a Telephone Receiver from Input Measurements

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The paper describes how an analysis of the functioning of a telephone receiver can be made by measuring the terminal electrical impedance of the receiver as a function of the length of a closed tube into which it works. With these data it is possible to calculate the excess pressure and the velocity of the air at the mouth of the receiver in relation to the voltage across the input terminals for any load condition. The analysis therefore furnishes means both for measuring acoustic impedance and for producing sound of known intensity.

INTRODUCTION

A METHOD of analyzing the operation of a telephone receiver, based upon electrical measurements of the input impedance for known acoustic loads, was originally used in an experiment for demonstrating certain acoustic phenomena in tubes. In the last few years the method has been developed to an extent where it has been of great value in a number of investigations in the acoustic laboratory. The method is particularly useful in that the complete performance of the receiver at any one frequency is determined from simple, easily-made measurements. Not only can the impedance of the air load on the receiver be found but also the amplitude and phase of the sound pressure in relation to the amplitude and phase of the terminal voltage.

The essential data for the analysis are obtained by measuring the electrical impedance at the input terminals of the receiver as a function of the length of a closed tube into which the receiver works when actuated by a sinusoidal voltage. The method can be applied directly to any form of electromagnetic sound-producing device which is adaptable for use with a horn. The application is simplest and the results are most satisfactory when a moving-coil type of device is used.

A closed air column of variable length has been widely used as a load on a receiver in making acoustical measurements. Kennelly and Kurokawa[1] appear to have been the first to make use of it. Very recently Flanders[2] describes a method of measuring acoustic impedance which also employs this type of load. The method about to be described has points of similarity with both of those cited, though the handling of the data is quite different in the three cases.

GENERAL THEORY

Before going into details it will be well to consider briefly the general theory on which this method is based. The theory is developed first for the case of an ideal receiver which has for a sound-producing surface the face of a rigid piston acting without air leakage at the mouth of the receiver. The force exerted on the mechanical system is considered to be applied directly to the piston, and the effective mechanical impedance of all the moving parts, including the reaction of the air, is considered to be concentrated at the piston. Finally, the receiver is one in which the back electromotive force generated by the motion is proportional at any frequency to the velocity of the piston.

If e = back e.m.f., and i = current in receiver, then ei is the power which at any instant is being transmitted to the mechanical system. Further, if F = force exerted on the mechanical system and v = velocity of piston, the power received by the

[1] A. E. Kennelly and K. Kurokawa, *Acoustic Impedance and its Measurement*, Proc. Am. Ac. Arts and Sci. **56**, 1 (1921).

[2] P. B. Flanders, *A Method of Measuring Acoustic Impedance*, Bell Sys. Tech. J. **11**, 402 (1932). Reprinted: J. Acous. Soc. Am. **4**, Supplement, July (1932).

mechanical system at any instant is Fv. Hence, $ei = Fv$.

It is necessary, of course, to use consistent units in this equation. Thus, if F is in dynes and v in cm per sec., absolute electromagnetic units should be used for e and i. By assumption, e is proportional to v, or in equation form, $e = kv$. Therefore:

$$F = ki \quad \text{and} \quad e/i = k^2/(F/v).$$

Let Z_M = mechanical impedance $= F/v$. Now e/i is that part of the electrical impedance which is due to the mechanical load. This we call the load impedance and designate by Z_{EL}. Then

$$Z_{EL} = k^2/Z_M.$$

The total impedance, Z_{ET}, measured at the input terminals of the receiver includes the impedance of the winding, Z_{EW}, as well as that of the load. Also, for purposes of analysis, the mechanical impedance is divided into the impedance of the air load, Z_A, and the piston impedance, Z_P.

Hence the complete expression for determining the performance of the receiver is:

$$Z_{ET} = Z_{EW} + [k^2/(Z_P + Z_A)].$$

If the parameters, Z_{EW}, k and Z_P, are independent of the air load, as is assumed to be the case in the moving-coil-type receiver, it is evidently possible with this equation to find the mechanical impedance of the air load from the measured terminal electrical impedance at each frequency for which these parameters have been determined. When the receiver is working into a closed tube, the impedance of the air load may be calculated from the dimensions of the tube and the frequency. The three parameters may be determined analytically from measurements of the terminal impedance, Z_{ET}, for three different known values of the air load impedance, Z_A. It is preferred, however, to handle the data by a graphical method. By employing this method a diagram is constructed which not only contains the required information in convenient form but also furnishes a check on the preliminary readings and indicates the extent to which various assumptions are justified.

Graphical Method

The graphical construction is here developed specifically for an ideal moving-coil-type receiver. As will be shown, this construction is directly applicable to the analysis of practical receivers of this type. In the moving-iron-type receiver there are iron losses which depend on the motion of the armature as well as on the current; hence the analysis is more complicated. Nevertheless, the same general procedure may be used to obtain a fairly complete analysis of a moving iron receiver as shown in Appendix I.

In the graphical analysis impedances are represented, as is customary, by plane vectors. The diagram will be developed in steps beginning with the load impedance and working back to the terminal impedance. When the load is an air column enclosed in a plugged tube, the impedance of the load will be purely reactive, provided no energy escapes through the tube walls or the plug, and provided no energy is absorbed in the air, a condition that can be closely approximated. Then the mechanical impedance is:

$$Z_M = Z_P + jX_A = R_P + j(X_P + X_A).$$

Hence Z_M is represented as in Fig. 1, the coordinates being in mechanical ohms.

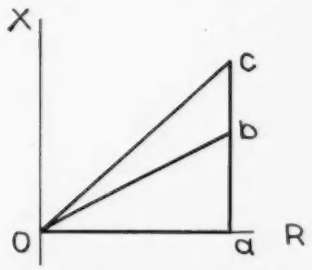

FIG. 1. $Oa = R_P$, piston resistance; $ab = X_P$, piston reactance; $Ob = Z_P$, piston impedance; $bc = X_A$, airload reactance; $Oc = Z_M$, total mechanical impedance.

If the tube length is varied, it will be shown that jX_A may have all possible values from $-j\infty$ to $+j\infty$. The locus of Z_M is then $R = R_P$; that is to say, the vector representing Z_M may terminate at any point on the line $R = R_P$. See Fig. 2. The corresponding load impedance is given by $Z_{EL} = k^2/Z_M$. It is a simple matter to prove that the locus of Z_E must be a circle tangent to the X axis at the origin, as shown in

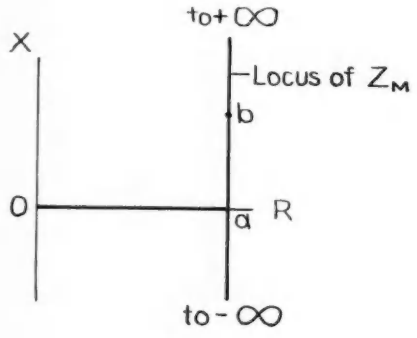

FIG. 2.

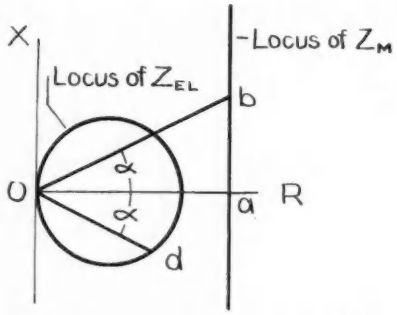

FIG. 3. Od = electrical impedance, when Ob = mechanical impedance.

Fig. 3. The proof is as follows:

$$R_P+jX=(k^2/(R_{EL}+jX_{EL}))$$
$$=(k^2R_{EL}/(R_{EL}^2+X_{EL}^2))$$
$$-(jk^2X_{EL}/(R_{EL}^2+X_{EL}^2)).$$

Therefore

$$R_P=(k^2R_{EL})/(R_{EL}^2+X_{EL}^2)=\text{constant}.$$

Therefore

$$R_{EL}^2-(k^2/R_P)R_{EL}+X_{EL}^2=0$$

or

$$[R_{EL}-(k^2/2R_P)]^2+X_{EL}^2=(k^2/2R_P)^2.$$

Thus the locus of $R_{EL}+jX_{EL}$ is a circle of radius $k^2/2R_P$ tangent to the X axis at the origin, as shown. The coordinates, R_E and X_E, of this circle are in electrical ohms. The magnitude of the circle depends on the scale which is chosen.

If now the vector Z_{EW} is added to this circle by moving the origin a distance $-Z_{EW}$, the circle becomes the locus of Z_{ET}; see Fig. 4. In this diagram three origins are shown as follows: O is the origin for Z_{ET}, O' is the origin for both Z_{EL} and for Z_M, and O'' is the origin for Z_A. The coordinate systems are labeled to correspond,

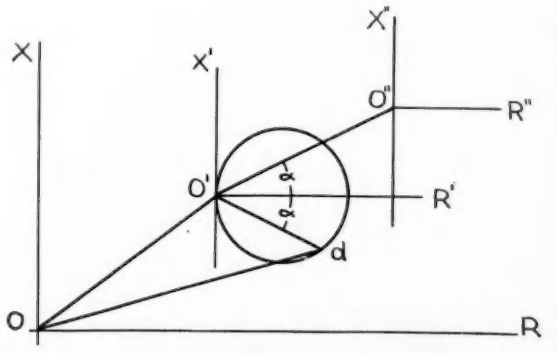

FIG. 4. XOR, reference axes, electrical impedance; $X'O'R'$, reference axes, electrical load, and mechanical impedance; $X''O''R''$, reference axes, air load impedance; $O'O''=Z_P$, mechanical impedance of piston; $O'd=Z_{EL}$, electrical load impedance, when $Z_M=O'O''$ or $Z_A=O$; $OO'=Z_{EW}$, electrical winding impedance; $Od=Z_{ET}$, total electrical impedance, when $Z_M=O'O''$.

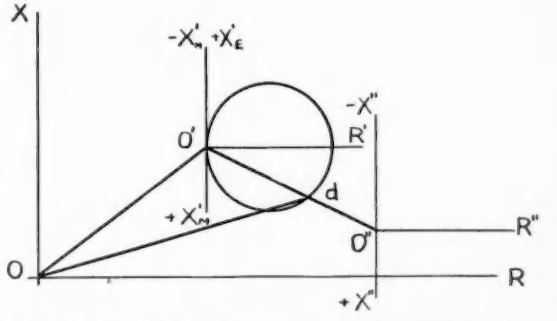

FIG. 5. $X'_EO'R'$, reference axes, electrical load impedance; $X'_MO'R'$, reference axes, mechanical impedance.

i.e., X' and R' are the axes for origin O', etc. As indicated on the diagrams, Figs. 3 and 4, the corresponding vectors representing Z_{EL} and Z_M make angles of the same magnitude but opposite sign with the axis of reals R'. That is, since

$$R_M+jX_M=\frac{k^2}{R_{EL}+jX_{EL}}=k^2\frac{R_{EL}-jX_{EL}}{R_{EL}^2+X_{EL}^2},$$

$$X_M/R_M=-X_{EL}/R_{EL}.$$

Hence Z_{EL} corresponding to Z_P (i.e., Z_M when $Z_A=0$) lies as shown.

It is more convenient to have the corresponding vectors coincide in direction. This will be the case if the axis of imaginaries for mechanical impedances is reversed. The final diagram will then have the form shown in Fig. 5. It will be seen that this diagram can be constructed for any receiver when Z_{ET} has been measured for the loads

$Z_A=\infty$ and $Z_A=0$. The diagram contains all the required information except that the scale of mechanical impedances is not known. This scale can be determined from one other measurement of Z_{ET} when Z_A has any known new value. The next step is to show how Z_A may be calculated from the dimensions of the air-column load.

Calculation of Air Impedance

Assuming a steady state of motion to have been established in the tube by an impressed sinusoidal force at the piston, the motion may be considered to be due to two plane progressive waves travelling in opposite directions. Since impedances have been represented by plane vectors we should, to be consistent, represent the excess pressure and particle velocity in the waves by rotating vectors, the real components of which represent actual values. Then the particle velocities in the incident and reflected waves are:

$$v_1=V_1e^{j(\omega t+\varphi)},\quad v_2=-V_2e^{j(\omega t-\varphi)},$$

where $\omega=2\pi f$, $f=$frequency, $t=$time, $\varphi=(2\pi l/\lambda)+\varphi_0$, φ_0 is a constant, $\lambda=$wave-length and $l=$length of air column measured from the plug to any point in the tube.

If the attenuation is negligible, the amplitudes V_1 and V_2 are constant. The sound pressure in the two component waves is then:

$$p_1=Z_ov_1,\quad p_2=-Z_ov_2,$$

where $Z_o=$the mechanical or acoustical impedance of a unit area of air column of infinite length.

The velocity and pressure at any point in the tube being the sum of their components, we have:

$$p=p_1+p_2=Z_o(v_1-v_2),\quad\text{and}\quad v=v_1+v_2.$$

If we let $V_1=V_0e^{\psi}$ and $V_2=V_0e^{-\psi}$, we get

$$p=Z_oV_0(e^{\psi+i\varphi}+e^{-(\psi+i\varphi)})e^{j\omega t}$$
$$=2Z_oV_0\cosh(\psi+j\varphi)e^{j\omega t}$$

and

$$v=V_0(e^{\psi+i\varphi}-e^{-(\psi+i\varphi)})e^{j\omega t}$$
$$=2V_0\sinh(\psi+j\varphi)e^{j\omega t}.$$

Hence the mechanical impedance of the air column whose area is a is:

$$Z_A=ap/v=aZ_o\coth(\psi+j\varphi).$$

If the plug which terminates the tube offers infinite impedance to the sound wave there will be no motion when $\rho=0$. Hence at the plug:

$$v=v_1+v_2=0.$$

Therefore

$$V_1e^{j(\omega t+\varphi)}=V_2e^{j(\omega t-\varphi)}$$

and

$$V_1=V_2;\quad\psi=0;\quad\text{and}\quad\varphi_0=0.$$

Hence

$$Z_A=-jaZ_o\cot(2\pi l/\lambda).$$

Thus Z_A depends on Z_o and quantities which are readily measured. The simplest evaluation of Z_o may be made from the relation $Z_o=\rho c$, where $\rho=$density of air, and $c=$velocity of propagation.

It makes little difference whether c is calculated for free air or measured in the tube, as it has been found that these values agree within one-half percent for tubes as small as $\frac{5}{8}$ inch diameter. It is usually simpler to use the measured value, i.e., λf, since f and λ are both required for other calculations. Under ordinary laboratory conditions $Z=41.0$ dynes/cm² divided by cm/sec. The variation is roughly $+0.06$ per mm rise in barometer from 760, and -0.07 per degree C rise in temperature from 20 degrees.

Application to Ideal Receivers

In making air-load-impedance measurements it is often convenient to use the infinite tube impedance, aZ_o, as the unit of measure. It is a particularly convenient value to use in determining the scale of mechanical impedances on the diagram. Thus, when the tube length is made $\frac{1}{8}\lambda$, $\frac{3}{8}\lambda$, etc., Z_A will be $+jaZ_o$ or $-jaZ_o$. The complete receiver diagram can then be constructed as shown in Fig. 6.

The lettered points are plotted from measurements made at the input terminals where the tube length has values as in Table I.

Table I.

Point number	l/λ	Z_A
O'	0 or $\frac{1}{2}$	∞
e	$\frac{1}{8}$	$-jaZ_o$
d	$\frac{1}{4}$	0
f	$\frac{3}{8}$	$+jaZ_o$

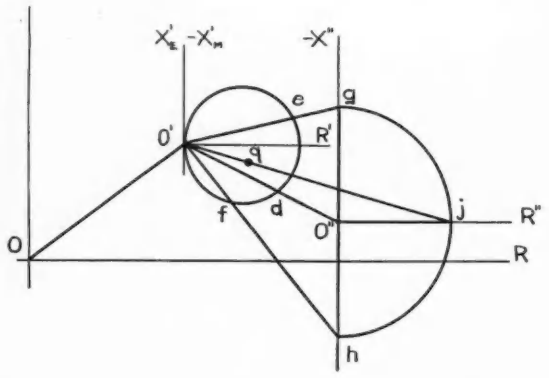

FIG. 6. $O''j$, $Z_A = Z_o a$; $O'j$, Z_M when $Z_A = Z_o a$; $O'q$, Z_{EL} when $Z_A = Z_o a$; $O'e$, Z_{EL} when $Z_A = -jZ_o a$; $O'f$, Z_{EL} when $Z_A = +jZ_o a$.

By projecting from O' through points e, d, and f onto the X'' axis drawn in any convenient place, the vector $(O''g)$ representing $-jaZ_o$ is found as indicated and its magnitude is checked by that of $(O''h)$ representing $+jaZ_o$.

The diagram is now complete. By its use, measurements of efficiency, impedance, or sound pressure may readily be made. The electrical efficiency may be defined as R_{EL}/R_{ET}, and the mechanical efficiency as R_A/R_M. The over-all efficiency is, of course, the product of these two.

The use of the diagram in finding the load impedance from the terminal impedance involves, in general, the calculation of the magnitude of Z_M corresponding to Z_{EL} from the relation $Z_M Z_{EL} = \text{constant}$. This constant may be found by multiplying the length $O'd$ by the length $O'O''$ as found from the diagram. The procedure in detail is as follows:

From the measured impedance, Oq, plot q. Scale off the load impedance $O'q$. Calculate the magnitude of the mechanical impedance $O'j$ and plot j on the line $O'q$ produced. The impedance of the air load is then given by $O''j$.

In the figure, this process is indicated for the case where the air impedance is that of an infinite column. It should be noted that a circular locus of Z_{EL} corresponds to a circular locus of Z_M. The proof is similar to that given above for the special case where the Z_M circle has an infinite radius.

The relation between the sound pressure at the piston and the voltage at the terminals is found most simply by starting from the relationship $F = ki$ which has been obtained above, when absolute electromagnetic units are used. For practical electrical units this becomes $F = ki(10^7)^{\frac{1}{2}}$ dynes, where k^2 is the product of corresponding values of Z_M in mechanical ohms (dynes $\div$cm/sec.) and Z_{EL} in ohms.

If p is the sound pressure in the air at the piston and a is the area of the piston $pa/F = Z_A/Z_M$ and if E is the voltage at the terminals $i = E/Z_{ET}$ amp. Hence

$$\frac{pa}{E} = \frac{Z_A}{Z_M}\frac{k(10^7)^{\frac{1}{2}}}{Z_{ET}} = \frac{Z_A Z_{EL}(10^7)^{\frac{1}{2}}}{kZ_{ET}} \text{ dynes/volt.}$$

This gives the relation between p and E both in amplitude and phase.

For the special case when there are standing waves in the tube and the diaphragm is at a pressure node, p will be zero at the diaphragm and cannot, therefore, be determined at any other point in the tube from this relation. We may, however, find the velocity at the diaphragm and work from that.

Since

$$pa/v = Z_A, \quad v/E = (Z_{EL}/kZ_{ET})(10^7)^{\frac{1}{2}}.$$

The values for p and v can then be found for other points in the tube from the equations developed previously.

ADAPTATION OF METHOD TO PRACTICAL RECEIVERS

The method of analysis which has been developed for an ideal receiver can be applied, directly or with modifications, to any practical receiver, provided the locus of the impedance vector measured as a function of the length of closed tube into which it works, is a circle.

Three types of receiver will be considered. In the moving iron type the analysis requires modifications which are described in Appendix I. If the sound producing element is a piston working in a tube with a small annular air space between piston and tube, another step is required in the analysis to take care of the effect of air leakage. This step is described in Appendix II. This type of receiver is of interest in that the mechanical damping can be so reduced that an overall efficiency greater than 80 percent is

realized under optimum conditions. The third type considered is a moving coil device actuating a diaphragm. This type is of greatest interest in that the analysis requires substantially no modification. Moreover, there are available receivers of this type which are admirably suited for making acoustical measurements by this method.

The treatment for this case is based on the assumption, experimentally justified, that the moving parts of the receiver and the air passage inside the mouth can be treated as a piston acting without leakage in a tube extending inside the mouth. The parameters of this equivalent piston will, of course, be functions of frequency. The equivalent-piston receiver must have the same power distribution and must give the same volumetric rate of air displacement as the actual receiver at every instant.

Let a_e = the effective area of the diaphragm. This is found by dividing the volumetric rate of air displacement by the velocity of the coil, v_c. Let v_p = velocity of equivalent piston, a = area of face of equivalent piston (area of tube), F_c = force on coil, F_p = force necessary to maintain motion of equivalent piston, and p = sound pressure on piston face. For equivalence:

$$v_c a_e = v_p a, \quad \text{and} \quad F_c v_c = (ap + F_p) v_p.$$

Hence

$$F_c/v_c = [(ap + F_p)/v_p](a_e/a)^2$$

or

$$Z_M = (Z_A + Z_p)(a_e/a)^2.$$

Substituting Z_M in basic equation gives:

$$Z_{ET} = Z_{EL} + [(k^2(a/a_e)^2)/(Z_p + Z_A)].$$

Since a/a_e is constant at any frequency, this equation is identical in form with the equation for the ideal receiver. The same graphical solution can be used by noting that the position of the plug in the tube which makes the air column impedance infinite is that position for which the measured resistance is a minimum.

Experimental Technique and Example

It has been found that certain precautions must be observed in order to obtain results which are consistent with the theory on which this method of analysis is based. The assumptions which have been made are considered to be justified to the extent that the values of air impedance found from the closed tube measurements check with the relation

$$Z_A = -jaZ_o \cot (2\pi l/\lambda).$$

The following experimental analysis of a receiver working into a horn will illustrate the uses of the method and some of the precautions which should be observed. The impedance at the throat of the horn, the efficiency of the receiver, and the actual pressure in the throat in terms of the electrical input will be obtained. The receiver used was a moving coil horn unit of standard make; the horn, a six-foot exponential trumpet. Measurements at 1200 c.p.s. will be described.

The impedance measurements may be made in any convenient manner; for the case described an impedance bridge was used, as shown in Fig. 7. Provision was made for a possible change in sign of the reactance of the receiver by including both a variable inductance and a condenser in the opposite arm of the bridge.

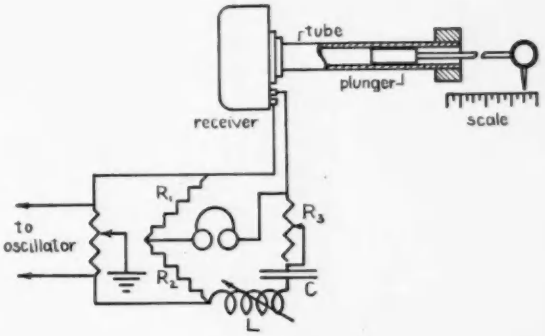

FIG. 7.

Before making the measurements the receiver was allowed to reach thermal equilibrium with its field excited, as both the field excitation and the mechanical properties of the diaphragm are functions of temperature. For the analysis of the receiver the air in a brass tube of $\frac{3}{4}$-inch inside diameter and $\frac{1}{16}$-inch wall was used as a load. A smoothly fitting brass plug $2\frac{1}{2}$ inches long formed the termination of this tube. As this formed a very efficient seal, it was necessary to move it carefully to prevent tearing the diaphragm by change in air pressure. For work of high precision it has been found necessary to imbed the tube in

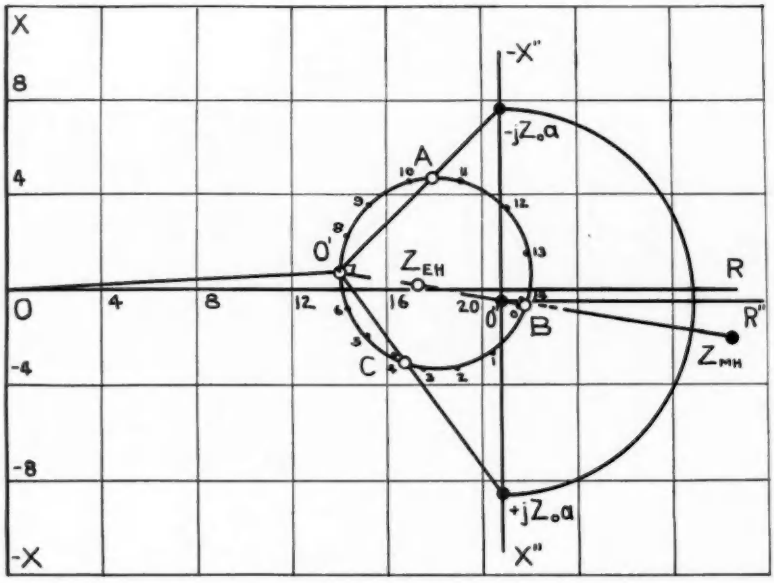

FIG. 8.

concrete to prevent its vibration; for ordinary measurements this precaution need not be taken. A weight clamped to the end of the tube may be used for this purpose also. It is desirable to use as low an input level as is consistent with the method of measurement to prevent overload of the receiver with its consequent distorting effects.

The input impedance was first measured as a function of the length of the terminating tube.

The values in Table II were observed. These points are plotted in Fig. 8.

TABLE II.

l	R	X	l	R	X
0	21.5	−0.6	8	14.3	+2.3
1	20.4	−0.7	9	15.3	+3.6
2	18.9	−3.3	10	17.0	+4.6
3	17.5	−3.3	11	19.1	+4.6
4	16.3	−2.7	12	21.1	+3.5
5	15.2	−1.9	13	21.9	+1.5
6	14.3	−0.8	14	21.6	−0.4
7	14.0	+0.8			

The minimum resistance occurs at $R=14$ ohms, $X=0.8$ ohm, which is therefore the impedance of the winding. The length of the tube between successive identical impedances is seen to be approximately 14.1 cm, and the length of tube at minimum resistance to be about 7 cm. The wave-length is thus $2\times14.1=28.2$ cm, and the equivalent length of tube between the diaphragm and the mouth of the receiver is $14.1-7.0=7.1$ cm. This is 0.254 wave-length, or 90.5°.

The key points are given in Table III.

TABLE III.

Point	Z_A	l/λ	l tube	R_E	X_E
C	$+jZ_0a$	$-\frac{1}{8}$	3.47	16.8	−3.0
O'	∞	0	7.00	14.0	+0.8
A	$-jZ_0a$	$\frac{1}{8}$	10.53	18.0	+4.8
B	0	$\frac{1}{4}$	14.05	21.9	−0.6

These points were verified and plotted as shown. The point of minimum resistance may be determined precisely by setting the inductance of the bridge to a point corresponding to the reactance of the center of the circle and adjusting the length of tube for a balance.

Next the circle is inverted as described, when using an arbitrary scale to set up the coordinate axes for the mechanical system.

The impedance of the receiver when working into the trumpet was $R=17.3$ ohms, $X=0.2$ ohm. This was plotted at Z_{EH} and inverted to the same scale as was used to determine the mechanical coordinate system. The impedance of the mechanical system when thus loaded is given by $O'Z_{MH}=(2+j.35)Z_0a$. Of this the impedance

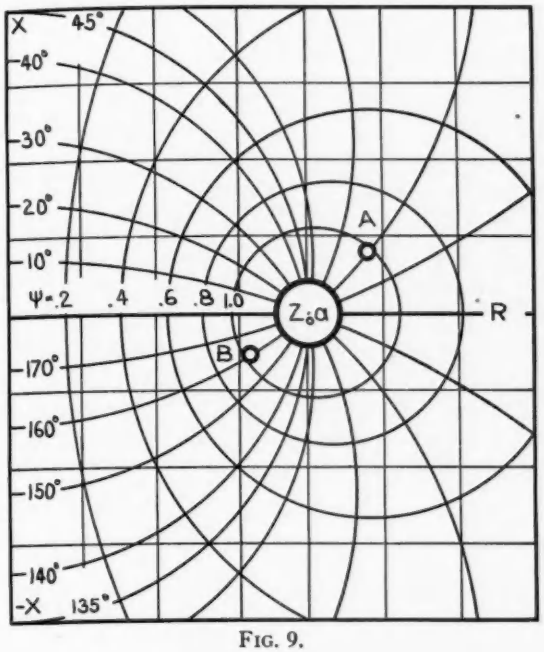

FIG. 9.

of the piston is $(O'O'')=(0.8+j.15)Z_oa$, and the impedance of the air load is $O''Z_{MH}=(1.2+j.2)Z_oa$. But this is the impedance of the air load at the diaphragm, and what is wanted is the impedance of the load at the mouth of the receiver, that is, at the throat of the horn. Recourse is now made to the relation developed between impedance and length of tube. This relation for impedance as a function of length of tube and reflection coefficient may be rewritten to express the relative impedance at various points:

$$Z_1/Z_2=[\coth(\psi+j\phi_1)/\coth(\psi+j\phi_2)].$$

According to the assumptions which have been discussed above, ψ remains constant and ϕ has decreased by 90.5° in moving from the piston to the mouth of the receiver. Part of a chart of the function $(A+jB)Z_oa=Z_oa\coth(\psi+j\phi)$ has been reproduced in Fig. 9. If now the impedance of the air load is plotted on this diagram at A, the impedance of the mouth of the receiver may be read directly by following the circle $\psi=$constant around to the point B, where $\phi=\phi_0-90.5°$. This is the actual impedance at the mouth of the horn and is equal to $(0.78-j.13)Z_oa$. This value might have been found analytically, but it is generally conceded that graphical methods, with available charts of hyperbolic functions, are simpler.

The electrical efficiency is given by the ratio of the load resistance to the total resistance, or $(17.3-14.0)/17.3=19$ percent. The mechanical efficiency is given by the ratio of air load to total resistance, or $1.2/2.0=60$ percent. The overall efficiency, from input terminals to acoustical output is the product of the two efficiencies, or $0.19\times0.60=11.4$ percent. In this connection, the effect of changing the air load resistance or the resistance of the diaphragm is of interest. Increasing the air load resistance will increase the mechanical efficiency but at the same time will produce a lower load resistance in the electrical system and therefore produce a lower electrical efficiency. Maximum efficiency will, of course, occur when the rates of change in the two systems are equal. Decreasing the mechanical resistance of the diaphragm, on the other hand, will not only increase the mechanical efficiency, but will also increase the electrical efficiency. Its importance is thus quite obvious.

Next we may apply the relation

$$pa/E=Z_AZ_{EL}(10^7)^{\frac{1}{2}}/kZ_{ET}$$

to find the pressure acting on the air at the diaphragm in terms of the applied voltage at the terminals of the receiver. Z_o may be assumed to be equal to 41 absolute mechanical ohms. The area of the tube used is 2.85 square cm. The characteristic impedance of the tube, Z_oa, is thus $41\times2.85=117$ mechanical ohms. The conversion constant k is the product of an impedance in the electrical system and the corresponding impedance in the mechanical system. The resistance of the piston (the R component of $O'O''$ in Fig. 8) is $0.8\times117=93.5$ mechanical ohms. In the electrical system this appears as the R component of $O'B$, and is 7.9 ohms. The conversion constant is thus $93.5\times7.9=738$.

With the receiver loaded by the horn,

$$Z_A=(1.2+j.2)Z_oa=140+j23.4,$$

$$Z_{EL}=3.3-j0.6,$$

$$Z_{ET}=17.3+j.8.$$

Hence, the relation between sound pressure and applied voltage is given by:

$$\frac{2.85p}{E}=\frac{(140+j23.4)(3.3-j.6)10^7}{(17.3+0.8)738}.$$

In magnitude, the ratio of pressure to voltage is 0.131×10^6[(dynes/cm²)/volt] and the phase of p is 3.4° behind E. If the pressure at some other point in the tube is desired (for example, at the mouth of the receiver) the relation $p=p_0\cosh(\psi+j\phi)$ may be used, where p_o is constant and ψ and ϕ have the same meaning and values as appeared in the expression for Z_A as a function of length of tube. Hence the ratio of the pressure at the mouth of the receiver to the pressure at the diaphragm is the ratio of the hyperbolic cosines of the angles appearing at those two points as indicated on the chart of the hyperbolic cotangent used to find the impedance of the mouth of the horn. Thus:

$$|p|\ \text{throat}=0.131\times10^6\left|\frac{\cosh\ (1.05+j2.80)}{\cosh\ (1.05+j1.24)}\right|$$

$$=0.157\times10^6\ [(\text{dynes/cm}^2)/\text{volt}].$$

Conclusion

The use of this method of analysis has been illustrated above for determining the behavior of an electromagnetic receiver, the actual sound pressure and velocity produced by the receiver, and the acoustical impedance of the load into which the receiver works. The method may be applied to a variety of related problems such as the measurement of absorption coefficients, the determination of velocity of sound transmission in a tube and, with a slight extension, to the determination of attenuation in a tube. In short, it may be used for all types of acoustical problems which can be stated in terms of acoustical impedance, pressure, or velocity at the source.

Appendix I. Adaptation of Method to Moving Iron Type Receivers

The foregoing method of analysis may be applied to receivers of the moving iron type provided certain assumptions can be sufficiently justified. It is assumed as before that the electrical and mechanical parameters are independent of the amplitude of either the impressed voltage or the motion of the diaphragm. For this type of receiver, this implies specifically that there is a constant equivalent resistance due to eddy current losses and, further, that the hysteresis loop of the flux linking the coil is substantially elliptical, that the shape does not vary, and that the size bears a constant relation to the magnitude of the current or displacement causing it. Under these conditions, the amplitude of the change in flux will bear a constant relation to the amplitude of the current or displacement and the phase of the flux will lag by a constant angle. The above conditions are found to be sufficiently well satisfied for useful measurements if the electrical input is kept at a low value. A criterion is that the locus of the impedance measured for reactive air loads be a circle, as in the moving coil type receiver.

The peculiarity of this case is that the iron losses due to flux changes are associated with both the electrical and mechanical systems since the changes in flux are in general caused by both electrical current and mechanical displacement. The total iron loss evidently depends not only on the amplitudes of the current and displacement but also on the phase relation between them. This leads to an apparent paradox in that, for certain load conditions, the resistance of the receiver is less than when it is blocked.

If the assumed conditions hold, the vector relation between a sinusoidal current and the force it produces may be written:

$$F=IKe^{-j\alpha},$$

where α indicates the phase lag due to iron losses. In the same manner the relation between the velocity and the voltage generated by the motion is:

$$E=VKe^{-j\alpha}.$$

From these expressions:

$$E/I=K^2e^{-j2\alpha}/(F/v)$$

or

$$Z_{EM}=K^2e^{-j2\alpha}/Z_M.$$

Hence, Z_{EM} is the total change in impedance due to the motion. It has been called by Kennelly and Kurokawa the motional impedance. The expression is similar to that derived for the load impedance of a moving coil type receiver except that the relation is complex. The effect of this complex factor appears in the diagram (Fig. 10) as a rotation of the mechanical coordinate system through the angle -2α. The point of infinite mechanical impedance no longer corresponds to the point of minimum electrical resistance on the circle but at the point of tangency with the X axis. This point, therefore, cannot be determined from the electrical measurements as before but must be found by actual measurement of the tube length or from measurements made when the diaphragm is blocked in some other manner.

The ratio of power delivered to the mechanical system, to total power input, is given by the ratio of R_{EM} measured along the tipped axis $O'R$, to R_{total} measured along the original electrical axis. Thus it appears that the sum of the apparent power lost in the electrical system plus the power delivered to the mechanical system is greater than the total power supplied. At points on the extreme left-hand side of the circle the total resistance when the receiver is

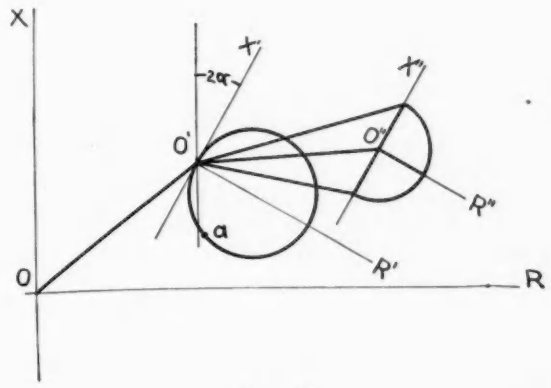

FIG. 10.

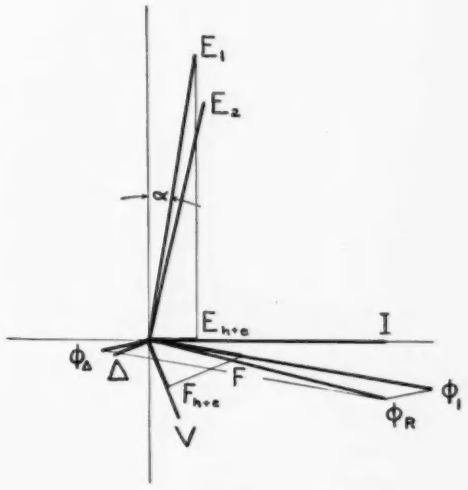

FIG. 11.

doing work in the mechanical system will be even less than the original resistance with the diaphragm blocked. The difference in power corresponds to the difference between the actual iron losses and the sum of the iron losses due to the current in the electrical system and the motion in the mechanical system acting independently.

It might further be argued, after an inspection of the diagram, that the circle will increase in size indefinitely as the resistance in the mechanical system is reduced, until not only is the iron loss nullified at points on the left-hand side of the circle, but also the actual ohmic loss in the winding. This condition is physically unrealizable, of course, because the resistance in the mechanical system resulting from the iron losses determines an absolute minimum, below which it is impossible to go. Thus a maximum size of impedance circle is determined such that the paradoxical situation just mentioned cannot arise.

The relations among the various vectors are sketched in Fig. 11, for the hypothetical case of a pure inertial load, (except for this hysteresis resistance) as an illustration of this limitation. The single requirement in setting up this diagram is that the component of force in phase with the velocity have the same magnitude relative to the velocity as the component of voltage in phase with current has to the current, in appropriate units, since the resistance due to hysteresis loss is the same. The effect of ohmic resistance in the winding has been neglected as its only effect is to shift the location of the reference axes for voltage in the electrical system.

E_1 is the applied voltage necessary to maintain a current I in the winding when the diaphragm is blocked. ϕ_1 is the resulting flux, and E_{h+e} the component of voltage in phase with the current to supply the iron losses. The force F_1 is in phase with ϕ_1. For an inertial load, V, the velocity will lag behind F at such an angle that the requirement mentioned above will be met. The deflection Δ is 90° behind the velocity, and the flux due to the displacement ϕ_Δ lags the displacement by the same angle that the flux due to current lags the current. The resultant flux is ϕ_R, and the corresponding voltage in the electrical system is E_2. If the vectors in the electrical system be divided by the current, the voltage vectors become the impedances under the two conditions, blocked diaphragm and reactive load. E_1 thus corresponds to OO' in Fig. 10 and E_2 to some vector such as $O'a$.

APPENDIX II. ADAPTATION OF METHOD TO RECEIVER WITH ANNULAR LEAKAGE AROUND PISTON

It is obvious that the most accurate determination of the output of a receiver can be obtained by this method of analysis if the receiver has high efficiency and is operated at a frequency near its mechanical resonance. In order, therefore, to produce a sound whose intensity can be ascertained most precisely, the device producing the sound should be so designed that it can be tuned to the frequency at which measurements are to be made. Moreover, the mechanical damping, R_P, must be reduced to a minimum if maximum efficiency is to be obtained. With these requirements in view, a receiver has been constructed which incorporates the following features. A moving coil acts directly on an aluminum piston which is supported by radial wires whose effective length can be varied. The mechanical damping in this construction is extremely low. The piston is mounted in a tube with a small clearance. No method could be found to seal this annular air space without introducing relatively great damping, hence the method of analysis was extended to take account of the sound which may leak by the piston. The additional steps in the analysis are given here. The device was found to be practical but somewhat difficult to use on account of extremely sharp tuning.

Assuming the effect of the annular leakage path on the air load to be equivalent to that of a branch tube entering the main tube at the piston face, the total admittance of the air load will be the sum of the admittance of the main air column and that in the equivalent branch tube. Mechanical admittance is defined as the reciprocal of mechanical impedance and designated by $Y=g+jb$.

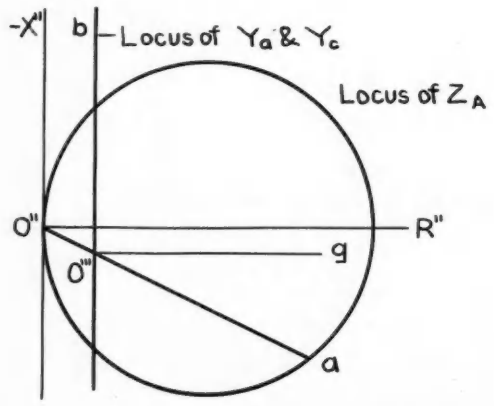

FIG. 12. When $Y_C=O$, $Y_A=Y_B=O''O'''$ and $Z_A=1/Y_A=O''a$.

Note: It is necessary to have O''' fall inside the circle to avoid having an inconveniently large scale for admittance since Y_B is essentially a small admittance.

Let Y_A=admittance of total air load on piston face, Y_B=admittance of air in equivalent branch tube, and Y_C=admittance of main air column, then: $Y_A=Y_B+Y_C$.

At any frequency, Y_B is constant provided the plug in the tube is not close to the piston face. For a closed air column, $Y_C=1/Z_c=(j/aZ_o)\tan(2\pi l/\lambda)$, hence if Y_C is plotted as a function of l on a coordinate system of mechanical admittances with an origin O''', the locus will be the line $g_c=0$ (see Fig. 12). The locus of Y_A will be the same line with respect to the origin O'' where $Y_B=O''O'''$, i.e., the line $g_A=g_B=$constant. Hence the locus of the air load impedance, $Z_A=1/Y_A$, will be a circle tangent to the X axis at O''. The proof for this construction has already been given in connection with finding the locus of Z_{EL}. If the X coordinates of mechanical impedances are reversed as before, corresponding values for Z_A and Y_A will lie on the same line through O''.

The original theoretical considerations may now be applied to complete the diagram. For the present case the circular locus of Z_A is finite instead of infinite but the corresponding locus of Z_{EL} can be proved to be another circle as before, but in this case the Z_{EL} circle does not pass through the origin O'. It is convenient to choose scales such that the Z_{EL} circle coincides with the Z_M circle. Then corresponding values of Z_{EL} and Z_M are represented by the two intersections with a line through O' and the circle.

The data required to determine this diagram completely

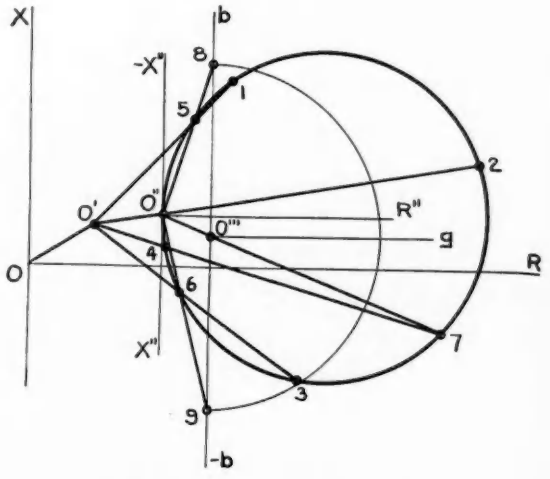

FIG. 13. Corresponding impedances.

Tube length	Z_{EL}	Z_M	Y_A	Y_C	Z_C
Piston blocked	O'				
$\lambda/8$	$O'1$	$O'5$	$O''8$	$O'''8$	$-jZ_oa$
$\lambda/4$	$O'2$	$O'O''$			O
$3\lambda/8$	$O'3$	$O'6$	$O''9$	$O'''9$	$+jZ_oa$
$\lambda/2$	$O'4$	$O'7$	$O''O'''$		∞

are the same as before with a slight modification in the procedure.

The impedance circle is determined as before, but points found for short air columns will not lie on the circle. The point O' is determined by the impedance measured when the receiver is blocked. A simple method for blocking the motion is to bring the plug in contact with the piston face. The point O'' is the point of minimum resistance on the Z_M circle. A line drawn from O' through O'' to intersect the circle at point (2), Fig. 13, determines the measured impedance corresponding to $Z_A=0$, i.e. to $Y_C=\infty$, hence the position of the plug can be found that corresponds to an effective length of air column of a quarter wave-length. This effective length has been found to differ slightly from the measured length, which fact may be attributed to a secondary effect of the peripheral leakage path. The scale of Y_C and the line $O''O'''$ are found as indicated in Fig. 13 from measurements made when the effective air column length is $\lambda/8$, $3\lambda/8$ and $\lambda/2$. Finally the air column impedances are found from the relation $Z_C=1/Y_C$.

Sound Absorption in Nonreactive Gas Mixtures

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(Received May 29, 1933)

IN a paper appearing in this journal under the above title,[1] Mr. Reed Lawlor has attempted to show that the absorption in a gas mixture of nonreactive gases depends linearly on their concentrations in disagreement with previous conclusions of mine.[2] Since a number of experimenters have implicitly accepted such a principle in the past it seems timely to discuss the matter here. I am constrained to the opinion that the previous analysis given by me is entirely valid and that Lawlor's findings are erroneous.

His argument, in brief, supposes a stratified medium in which alternate layers are gases A and B, respectively, both under the same T and p conditions. His paper proceeds with the assumption that a perfect mixture is obtained by increasing the stratification with given total volume constant and that on neglecting inter face effects[3] the behavior of a mixture can be calculated from this idealized representation. The immediate objection is that even in the limiting case of strata width of the order of molecular size the striated struction still obtains and because of this and the neglect of interface conditions the collisions between A and B type molecules are barred out—that is to say only $A-A$ and $B-B$ collisions are taken account of. Naturally then, linear relationships for most of the gas mixture characteristics will be established by this sort of reasoning, for one is at all times dealing with two pure gases. As an instance of this last remark consider the velocity of sound in a gas mixture as calculated on Lawlor's assumptions.

Suppose then a container of length d of which the part $rd(0<r<1)$ is filled with gas A and $(1-r)d$ with gas B, and imagine a nonphysical perfectly transparent, though impervious, membrane to separate the two gases. In the notation V_A, V_B, for the velocity in gases A, B and V_{AB} for the average velocity for traversing the length d, we have

$$d/V_{AB}=rd/V_A+(1-r)d/V_B. \qquad (1.00)$$

Imagine now a redistribution so that the ranges 0, r^2d; $(1-r)d$, $(1-r)(1+r)d$ contain gas A and the ranges r^2d, $(1-r)d$; $(1-r)(1+r)d$, d gas B; then the new average velocity denoted by V'_{AB} is such that

$$\frac{d}{V'_{AB}}=\frac{r^2d}{V_A}+\frac{((1-r)-r^2)d}{V_B}=\frac{d}{V_{AB}}, \qquad (1.1)$$

i.e., $$V'_{AB}=V_{AB}. \qquad (1.11)$$

Clearly this equality is independent of further increase in number of strata. Thus we are led to the conclusion that the reciprocal velocity in a mixture is a linear homogeneous function of the reciprocal velocities of the components as expressed in (1). In reality, though, the low frequency velocity, in a mixture, as a special instance, either as calculated on a macroscopic theory (cf. II) or on a microscopic basis as developed in my papers on this subject is given by the Laplace result—*viz.*

$$\frac{1}{V_{\text{mixture}}}=\left[\left(\frac{m_1N_1+m_2N_2}{kT}\right)\left((3/2)R+\frac{N_1C_1+N_2C_2}{N}\right)\Big/\left((5/2)R+\frac{N_1C_1+N_2C_2}{N}\right)\right]^{\frac{1}{2}}=\left(\frac{\bar{m}}{kT}\frac{\bar{C}_V}{\bar{C}_p}\right)^{\frac{1}{2}}. \qquad (1.2)$$

[1] Reed Lawlor, J. Acous. Soc. Am. **IV**, 284 (1933).

[2] D. G. Bourgin, Phil. Mag. **7**, 821 (1929); Phys. Rev. **34**, 521 (1929); J. Acous. Soc. Am. **IV**, 108 (1932); Phys. Rev. **42**, 721 (1932). These papers will be referred to as I, II, III, IV, respectively. The discussion of mixtures is to be found in I, II and a correction in reference 2 of III.

[3] The reflection and phase changes at the interfaces become increasingly important as the number of strata is increased. All wave analyses for propagation in dispersive media consider the emergent wave as the resultant of the primary and secondary wavelets. Both velocity and absorption are intimately connected with phase relation-

Cf. Eq. (4) for the definition of C_1 and C_2.

Eq. (1.2) is altogether out of accord with Eq. (1) and indicates the nonlinear dependence of the resultant reciprocal velocity on the relative concentrations.

It seems advantageous for experimental verification to write the formula for the absorption given in II in more familiar notation and incidentally give the complete expression for the velocity and absorption before the approximations, ordered as to the magnitude of ν, are made. For the meaning of most of the symbols and the basic equations the reader is referred to II where the case of an n gas mixture is taken up. When the discussion is restricted to a two gas mixture (cf. Eq. (5) of II and note 2 of III) the central formula in that paper may be written (by neglecting viscosity and conduction terms):

$$V^2=\frac{SkT}{N}\left[\frac{Nk(5/2)j\nu+(3/2)k(\sum_1^2(1-\omega_W)\phi_W)}{Nk(3/2)j\nu+(3/2)k(\sum_1^2(1-\omega_W)\phi_W)}\right] \tag{2.00}$$

with N/S = mean molecular mass (cf. reference 2 of III) and $j=(-1)^{\frac{1}{2}}$. From Eq. (3.1) of II we copy

$$(1-\omega_W)\phi_W=\sum_1^2\frac{\frac{2}{3}\beta_W N_W j\nu}{1+j\nu/\sum_1^2(L_{WR}N_R/\frac{2}{3}\beta_W)}. \tag{3.}$$

Let us introduce C_W as the specific heat of the internal energy states of gas W (i.e., $=kN\beta_w$), then, recognizing Nk as R the ordinary gas constant the well-known relations may be written

$$\begin{aligned}(C_v)_{\text{gas }W}&=C_W+(3/2)R;\\(C_p)_{\text{gas }W}&=C_W+(5/2)R.\end{aligned} \tag{4.}$$

After a little algebra there is obtained

$$V^2=\frac{SkT}{N}\left[1+\frac{R}{(3/2)R+\frac{1}{N}\sum\frac{N_WC_W}{1+j\nu/\sum N_R\Gamma_{WR}}}\right], \tag{2.1}$$

where

$$\Gamma_{WR}=L_{WR}/\tfrac{2}{3}\beta_W.$$

With $V^{-1}=V_r^{-1}+(-1)^{\frac{1}{2}}V_i^{-1}$ the damped sound wave may be expressed

$$A(x,t)=A_0e^{-x\nu/V_i}\sin\nu(t-x/V_r). \tag{6}$$

The absorption coefficient is usually defined as either $2/V_i\nu$ or $2\nu^2/V_i$ (the factor 2 enters on assuming the intensity to vary as amplitude[2]). In order to bring out the analogy with the Laplace formula Eq. (2.1) is written as

$$\frac{1}{V^2}=\frac{N}{SkT}\left\{\frac{\tilde{C}_V-j\nu D}{\tilde{C}_p-j\nu D}\right\}, \tag{2.2}$$

where

$$\tilde{C}_V=(3/2)R+\frac{1}{N}\left(\frac{N_1C_1}{1+\nu^2/N_1\Gamma_{11}+N_2\Gamma_{12}}+\frac{N_2C_2}{1+\nu^2/N_1\Gamma_{21}+N_2\Gamma_{22}}\right),$$

$$\tilde{C}_p=(5/2)R+\frac{1}{N}\left(\frac{N_1C_1}{1+\nu^2/N_1\Gamma_{11}+N_2\Gamma_{12}}+\frac{N_2C_2}{1+\nu^2/N_1\Gamma_{21}+N_2\Gamma_{22}}\right),$$

$$D=\frac{1}{N}\left[\frac{N_1C_1}{N_1\Gamma_{11}+N_2\Gamma_{12}}+\frac{N_2C_2}{N_1\Gamma_{21}+N_2\Gamma_{22}}\right]=\left\{\frac{N_1C_1}{\bar{\Gamma}_1}+\frac{N_2C_2}{\bar{\Gamma}_2}\right\}\frac{1}{N^2}.$$

Application of de Moivres theorem to Eq. (2.2) gives[4]

ships among these waves—hence neglect of an important class of secondary waves is indefensible in calculations of either.

[4] Although these formulae are derived without any approximation from Eq. (2) the assumptions involved in Eq. (2) restrict its validity, and accordingly that of Eqs. (7) and (7.1), to frequencies below that of the first sound absorption band of either gas (cf. IV).

$$\frac{1}{V_R}=\left[\frac{N}{SkT}\frac{((\bar{C}_p\bar{C}_V+\nu^2D^2)^2+\nu^2D^2R^2)^{\frac{1}{2}}}{(\bar{C}_p{}^2+\nu^2D^2)}\left(\tfrac{1}{2}+\left\{\frac{\bar{C}_p\bar{C}_V+\nu^2D^2}{2[(\bar{C}_p\bar{C}_V+\nu^2D^2)^2+\nu^2D^2R^2]^{\frac{1}{2}}}\right\}\right)\right]^{\frac{1}{2}}.$$

$$\frac{1}{V_i}=\left[\frac{N}{SkT}\frac{((\bar{C}_p\bar{C}_V+\nu^2D^2)^2+\nu^2D^2R^2)^{\frac{1}{2}}}{(\bar{C}_p{}^2+\nu^2D^2)}\left(\tfrac{1}{2}-\left\{\frac{\bar{C}_p\bar{C}_V+\nu^2D^2}{2[(\bar{C}_p\bar{C}_V+\nu^2D^2)^2+\nu^2D^2R^2]^{\frac{1}{2}}}\right\}\right)\right]^{\frac{1}{2}}. \tag{7}$$

As an approximation the denominator of the second term in the last bracket may be expanded by the binomial theorem and gives

$$\frac{j}{V_i}=\tfrac{1}{2}\left(\frac{N}{SkT}\right)^{\frac{1}{2}}\left[\frac{\nu DR\left(1+\frac{1}{4}\frac{RD\nu}{(C_pC_V)^{\frac{1}{2}}}\right)}{(\bar{C}_p\bar{C}_V+\nu^2D^2)^{\frac{1}{2}}(\bar{C}_p{}^2+\nu^2D^2)^{\frac{1}{2}}}\right]=\frac{j\nu}{2\bar{V}_0}\left[\frac{DR}{\bar{C}_p\bar{C}_V+\nu^2D^2}\right]\left[1+\tfrac{1}{4}\frac{\nu RD}{C_p{}^{\frac{1}{2}}C_V{}^{\frac{1}{2}}}\right] \text{ where } j=(-1)^{\frac{1}{2}} \tag{7.1}$$

where $\bar{V}_0{}^{-1}$ is the value of $V_r{}^{-1}$ to the same approximation. Making a further approximation for ν small this is nearly[5]

$$\frac{j}{V_i}=\frac{j\nu[\overline{m}/kT]^{\frac{1}{2}}[N_1C_1/\bar{\Gamma}_1+N_2C_2/\bar{\Gamma}_2]k}{2(\bar{C}_p{}^3\bar{C}_V)^{\frac{1}{2}}}$$

or, written in full,

$$\frac{1}{V_i}=\frac{\nu k}{2}\left[\frac{N_1m_1+N_2m_2}{NkT}\right]^{\frac{1}{2}}\left[\left(\frac{N_1C_1}{N_1\Gamma_{11}+N_2\Gamma_{12}}+\frac{N_2C_2}{N_1\Gamma_{21}+N_2\Gamma_{22}}\right)\Big/\left((5/2)R+\frac{C_1N_1+C_2N_2}{N}\right)^{\frac{1}{2}}\left((3/2)R+\frac{C_1N_1+C_2N_2}{N}\right)^{\frac{1}{2}}\right]. \tag{7.2}$$

The corresponding expression for a pure gas is, to the same approximation,

$$\frac{1}{V_i}=\nu\left(\frac{m}{kT}\right)^{\frac{1}{2}}\frac{RC/N\Gamma_{11}}{(C_p{}^3C_V)^{\frac{1}{2}}}=\nu\left(\frac{m}{kT}\right)^{\frac{1}{2}}\left[\frac{RC/N_1\Gamma_{11}}{C_pC_V}\right]\frac{1}{V_0}. \tag{7.3}$$

As already pointed out in I and II the nonlinearity of $V_i{}^{-1}$ as dependent on the concentrations is obvious. (Compare Eqs. (7.1) and (7.2)). One datum given by experiment at low supersonic frequencies is the relation between Γ_{ij} and Γ_{jj}.[6] A direct way of ascertaining these values in practice is to use an auxiliary variable ρ defined by the equation

$$\rho=1/V_i(\bar{C}_p{}^3\bar{C}_V/\overline{m})^{\frac{1}{2}} \quad \text{or} \quad f(\rho,\ N_1/N_2)=0.$$

In general $f(\rho,\ N_1/N_2)=0$ is a cubic equation (cf. Eq. (7.2)) but in the particular case $\Gamma_{11}=\Gamma_{12}$, $\Gamma_{21}=\Gamma_{22}$ the second and third degree terms drop out.

The present status of the absorption[7] (and velocity) theory for mixtures is that of a 'first-order' theory in the sense of IV—that is to say the lag parameters ω_1 and ω_2 are supposed independent of the internal states. The extension which could provide a deeper theoretical basis for experimental work in the neighborhood of sound absorption bands would take into account the dependence of the ω's on the internal state after the model calculation given in IV for a single gas.

[5] It is easily verified that, except for notation, this is the value given by Eq. (5.2) of II.

[6] The values of Γ_{11} and Γ_{22} are, of course, obtainable from single gas measurements.

[7] In analyzing data on CO_2 and air (cf. Lawlor's paper) it is clear that two types of absorption are involved. That in CO_2 is predominantly the internal state lag effect which I have studied in my papers, while air shows mostly viscosity and conduction influence for the frequencies used. For meaningful deduction it is necessary to eliminate these latter effects—possibly by comparison with an inert or rare element gas having approximately the same viscosity and conductivity characteristics but no appreciable absorption of the first type. In this connection, cf. Kneser, Ann. d. Physik **12** (1931).

Erratum: On Minimum Audible Sound Fields

(J. Acous. Soc. Am. **4**, 288, 1933)

The equation on page 299 should read

$$R=\left[\frac{\int_0^{2\pi} F_\theta^2 \cdot d\theta}{2\pi F_0^2}\right]^{\frac{1}{2}}$$

instead of

$$R=\left[\left(\int_0^{2\pi} F_\theta^2 \cdot d\theta\right)\right]^{\frac{1}{2}} \Big/ 2\pi F_0^2.$$

L. J. Sivian and S. D. White

Bell Telephone Laboratories,
New York

News and Notes

Meeting of the Society

THE Acoustical Society of America held its semi-annual meeting in Washington, May 1 and 2, at the Bureau of Standards. Eighteen papers were presented on various acoustical subjects. A Symposium on Sound Ranging included three invited papers,—*Physical Methods of Exploration for Oil Bearing Structures*, by E. R. Shepherd; *Recent Developments in Generators and Receivers of Directive Sound Signals in Air*, by H. C. Hayes: *Sound Ranging at the U. S. Coast and Geodetic Survey*. An evening lecture on Nature's Music was given by W. J. Humphreys of the Weather Bureau. Officers elected for next year are as follows:—*President*, V. O. Knudsen; *Vice-President*, H. A. Frederick; *Secretary*, Wallace Waterfall; *Treasurer*, E. E. Free; *Members of Council:*—E. W. Kellogg, F. A. Saunders, F. A. Firestone, G. Oscar Russell, E. C. Wente, P. E. Sabine. The next meeting of the Society will be held in Chicago, December 4 and 5.

The Constitution and By-Laws of the Society were amended to provide that the Editor should be an elected officer of the Society and also that he should be a member of the Council. Professor Watson was appointed by the Council as Editor for the coming year. The new amendments to the Constitution and By-Laws provide that the Editor shall choose an Editorial Board consisting of five persons and shall submit the names to the Council for approval.

Elmer Edgar Hall

Professor Hall, Chairman of the Physics Department, University of California, died on November 19, 1932. Professor Hall was a pioneer in acoustical activities, and for many years was the leading consultant in California for acoustical problems. His investigational work on vibrations of buildings in San Francisco was published in the *Electrical World* in 1915, and furnished valuable information regarding protection against earthquakes. He was also active in promoting acceptable acoustics in buildings and auditoriums. He supported the Acoustical Society in its organization and subsequent development.

In later years, his administrative duties as Chairman of the Physics Department occupied most of his time. The success of this Department and its gratifying prominence in the scientific world are due largely to the diplomacy and judgment of Professor Hall.

F. R. Watson

Program of the Ninth Meeting of the Acoustical Society of America

MAY 1–2, 1933

East Lecture Room, Bureau of Standards

WASHINGTON, D. C.

MONDAY, MAY 1ST, 1933, 10:00 A.M. Eastern Standard Time

1. The Theory of Sound Radiating Walls of Voice Tubes. A. PRESS, *Graduate School of New York University.* Introduced by L. B. HAM.

The effects of the sound radiation of energy by the walls, and of the energy consumption by virtue of mechanical hysteresis, have been introduced into the Theory of Sound. The exponential formula of Lord Rayleigh has been found to be but an approximate case of the more general solution obtained for a voice tube or pipe. A new operational algebra has also been invented for simply and compactly applying the boundary conditions to the more general equation of sound, *viz*:

$$\frac{\partial^2 p}{\partial x^2} - h\frac{\partial^2 p}{\partial t^2} + k\frac{\partial^3 p}{\partial t^3} = 0.$$

The wall flexibility constant h and the energy consumption constant k have been evaluated by means of the Bureau of Standards experiments of Messrs. Eckhardt, Chrisler, Quayle, Evans and Buckingham as given in Technological paper No. 333. Methods are also indicated for arriving at such constant determinations by other experimental means. The influence of sound energy consumption on the distance between nodes is brought out as well as the fact that no absolute nodal condition becomes physically possible despite the effects of travelling waves set up along the voice tube or pipe.

2. A New Analyzer for the Audible Frequency Range. H. H. HALL AND D. G. CLIFFORD, *Harvard University.*

This instrument was designed for comparatively rapid analysis of sound spectra produced by musical instruments. It is a heterodyne analyzer using an intermediate frequency of 20 kilocycles per second. The filter is a magnetostrictive resonator of very low decrement capable of distinguishing between two frequency components only forty cycles per second apart while differing by some fifty decibels in amplitude. The amplitudes are measured by a logarithmic voltmeter controlling a cathode-ray oscillograph which records their relative magnitude, calibrated directly in decibels, on a strip of photographic paper. The recording camera is geared to the oscillator which furnishes the heterodyne frequency in such a way that the audible range up to 10,000 cycles per second may be swept out in a comparatively short time. Every effort has been made to reduce the duration of transients in the system. Preliminary tests indicate that a complete analysis may be made in about twenty seconds.

3. An Experimental Study of the Rôle of the Tympanic Membrane and the Ossicles in the Hearing of Certain Subjective Phenomena. DON LEWIS AND SCOTT REGER, *The State University of Iowa.* Introduced by C. E. SEASHORE.

It is usually contended that so-called subjective tones are due to vibrations introduced either by asymmetrical action of the tympanic membrane or by nonlinear functioning of the ossicles. The experiments here reported were designed to determine whether the tympanic membrane and the ossicles play any part in the generation of these phenomena. Individuals who had neither tympanic membranes nor ossicles served as observers. The harmonic constitution of each of the complex tones used as stimuli was such as to make the fundamental tone audible to the normal ear, when it was absent and only two or more overtones were present. It was easy to discover whether or not an observer heard this fundamental tone by having him match the pitch of the complex tone with a pure tone produced by a beat-frequency oscillator. The harmonics present in each of the complex tones was determined by means of harmonic analysis. The results of the investigation indicate that the tympanic membrane and the ossicles are probably not involved in the hearing of subjective tones.

4. The Ventricular Bands and the Physiology of the Voice. E. M. JOSEPHSON, M.D. AND LOUIS SIMMIONS, *New York City.*

Recent studies in the anatomy of the ventricular bands and of the thyro-arytenoid muscles, and

physiologic researches in the mechanics of the larynx have compelled changes in concept of voice formation.

These studies have revealed the presence of structures which have been overlooked which impart to the false vocal cords an independent motility and an action antagonistic to that of the thyro-arytenoid muscles; and which actively alter the conformation of the Sinus Morgagni. These studies stress the hitherto unemphasized importance of the function of the suspensory mechanism of the larynx, and the interrelation of the motor mechanisms of respiration and voice formation.

Clinical studies prove that ventricles of the larynx play an important rôle in the formation of the human voice. Filling of the ventricles by disease processes which do not in any wise impair the motility of the true vocal cords or their freedom to vibrate, nevertheless results in complete or high-grade aphonia and dysphonia. Similar disorders are associated with disease of the ventricular bands. These studies indicate the need of extensive researches in the mechanism of the voice; for they contradict much that has been written and dogmatically taught on the subject of the voice. (Slides will be shown.)

5. Some Notes on the Character of Bell Tones. A. N. CURTISS, *R.C.A. Victor Company, Inc.* AND G. M. GIANNINI, *Curtis Institute of Music.*

This paper presents some new data on the frequency and position of the partials of a bell. The decrement curve of the sound and the fine structure of the component tones are discussed and the description of the apparatus used in the experiments follows. Modifications in the design of bells are proposed in order to lessen the criticisms on present types of carillons.

MONDAY, MAY 1ST, 1933, 2:00 P.M.

SYMPOSIUM ON SOUND RANGING

6. Physical Methods of Exploration for Oil-Bearing Structures. E. R. SHEPARD, *Bureau of Standards.*

Modern scientific methods of prospecting for oil will be described and illustrated. These employ both natural and artificially produced forces. The former include gravitation, magnetism, galvanic potentials, radioactivity, and heat generation; while among the more important of the latter are seismic waves caused by an explosion and electric currents used in the study of the electrical resistivity of the earth.

A detailed description of the seismic method will be given particularly as it is used for determining the location of oil bearing salt domes on the Gulf Coast. In this method a charge of dynamite is exploded in the ground and the resulting waves through the earth are picked up by geophones at several points and recorded on an oscillograph film. The ground waves travel with different velocities, depending upon the character of the strata through which they pass. Because of the relatively high velocity of the waves through salt and stone, such mediums are easily detected.

A number of slides will depict different geologic formations with which oil is associated, while others will show seismic apparatus and the technique employed in locating the oil-bearing structures.

7. Recent Developments in Generators and Receivers of Directive Sound Signals in Air. H. C. HAYES, *Naval Research Laboratory.*

Certain problems peculiar to the Navy in process of solution at the Naval Research Laboratory, Anacostia, D. C. have called for the generation and reception of powerful directive sound signals in air. This paper describes apparatus developed for this purpose, and discusses briefly some of the applications. A working model of the apparatus will be demonstrated.

8. Sound Ranging at the U. S. Coast and Geodetic Survey. HERBERT GROVE DORSEY.

At this Bureau sound ranging is utilized in both the vertical and horizontal directions. The former, or echo method of depth measurement, was started in 1923 with the Sonic Depth Finder, which uses a method of regulating the rate of sending signals until the outgoing signal is binaurally heard to coincide with the incoming echo. From the rate of sending the depth is calculated. This method was displaced by the Fathometer when it was placed on the market in 1925. The Fathometer is direct reading by visual indications, the time elapsed between the outgoing signal and received echo being measured by the angle through which a neon tube has rotated during the interval. Fathometers are now used on practically all Coast Survey Ships.

The success of sound ranging in the vertical direction suggested its use in the horizontal direction and the method was developed early in 1924 with the cooperation of the Bureau of Standards. By this method a chronograph on the surveying ship records the explosion of a small bomb of TNT, the sound of which goes to two or more hydrophone stations and automatically causes the emission of radio signals which are recorded on the same chronograph. Such methods are now extensively used by Coast Survey Ships to locate their position in areas beyond the sight of land.

MONDAY, MAY 1ST, 1933, 8:15 P.M.

SPECIAL LECTURE

9. Nature's Music. W. J. HUMPHREYS, *Weather Bureau.* Illustrated with slides.

TUESDAY, MAY 2ND, 1933, 10:00 A.M.

10. Measurement of Sound Absorption by a Modified Tube Method.* K. C. MORRICAL AND F. R. WATSON, *University of Illinois.*

Measurements of the sound absorbed by small samples of material one foot square were obtained for five pitches,—4096, 2048, 1024, 512, 256, with numerical calculations of coefficients for the three higher pitches. Diffraction effects at the pitches 512 and 256 made the calculations uncertain. Sound from an electrodynamic loudspeaker passed through a cast iron tube 8 inches in diameter and 2 feet long where it impinged on the material placed at an angle of 45° to the axis of the tube. It was thus reflected so as to pass at right angles to its original direction through a side opening in the tube to a condenser microphone where it was measured. The path from the material to the microphone was enclosed by a tube of ground cork 2 inches thick held in place by porous metal screening. Additional measurements were taken with the sample removed (theoretically, 100 percent transmission, 0 percent reflection) and also with a thick glass plate replacing the material (100 percent reflection). Further experiments are in progress to get coefficients at the lower pitches.

* Part of an investigation financed by the United States Gypsum Company.

11. On Frequency Modulated Signals in Reverberation Measurements. F. V. HUNT, *Harvard University.*

A point-by-point curve tracer, similar to that described by Norris and Andree [J.A.S. 1, 366 (1930)] but permitting a longer period of decay to be traced, is employed to study the reverberant decay of pure tones and tones having various degrees of frequency modulation (so called "warble" tones). Straight lines (db *vs.* time) are fitted to the decay curves by the assumption that the slope determined by *every* pair of points should be weighted in the average according to the decay time included between the two points. This leads to a simple numerical procedure when the points are equally spaced on the time axis.

The deviations of individual points from the best straight line are computed and found to fall into regular and consistent time patterns, from which large group deviations can be seen to gradually disappear as the degree of warble is increased. These time patterns differ from point to point in the sound chamber but the magnitude of the deviations and the slope of the decay curves (within a limit of accuracy consistent with the deviations) is practically independent of position.

Conclusions are drawn regarding the accuracy with which decay rates can be determined using pure and warble tones.

12. Experimental Evidence of Nonlogarithmic Sound Decay. V. L. CHRISLER AND CATHERINE MILLER, *Bureau of Standards.*

In this paper experimental data are presented showing that in a room containing the average acoustical installation the distribution of sound energy does not remain uniform as the sound decays. In consequence the decay of the sound energy is not logarithmic. As one of the fundamental assumptions in all reverberation theories is that the sound energy does decay logarithmically and that it remains uniformly distributed during the decay, it is evident that the reverberation formulae as now given do not apply in most cases. The error introduced in computing the reverberation time where there is a ceiling treatment only may be as much as 30 percent.

It should be possible by further study of this problem to introduce some form of a correction factor in the present formulae so as to take care of most cases encountered in practice.

13. Measurement of the Rate of Decay of Sound in Small Chambers for Frequencies to 11,000 cycles, and a Determination of the Effects of Temperature and Humidity on the Absorption of Sound in Air. VERN O. KNUDSEN, *University of California at Los Angeles.*

A modification of the Norris-Andree method of measuring the rate of decay of sound in small chambers has been developed which operates satisfactorily for frequencies up to 11,000 cycles. The rate of decay, in db per second, in cubical chambers 6 feet and 2 feet on an edge, is accurately linear over a range of at least 60 db. The equipment has been used to determine the effects of temperature and humidity on the absorption of sound in air. The results obtained confirm those obtained by the author two years ago, but the measurements have been extended to higher frequencies, to dryer air, and to temperatures between 0 and 70°C. The results exhibit further evidence of the absorption of sound owing to the transfer of energy by collisions of H_2O and O_2 molecules (see abstract by H. O. Kneser, Bull. Am. Phys. Soc. for Washington meeting, April, 1933). The apparatus also is convenient for measuring the absorption coefficients of small samples of acoustical materials, especially at high frequencies.

TUESDAY, MAY 2ND, 1933, 2:00 P.M.

14. A High Speed Level Recorder and Some of Its Uses in Acoustical Measurements. E. C. WENTE, E. H. BEDELL AND K. D. SWARTZEL, JR., *Bell Telephone Laboratories.*

A device has been developed which will record the intensity of audiofrequency currents directly on a moving strip of paper by means of a stylus. A wide range of intensities may be covered and the deflection of the stylus is proportional to the logarithm of the input current; the recorder thus has a uniform scale in decibel units. It is capable of following fluctuations in the input current up to 150 per second, and will follow changes in intensity at a rate up to 240 db per second. When used in conjunction with a microphone the recorder lends itself to many types of acoustical measurements. It has been extensively used for reverberation time measurements for which it is particularly well adapted because it will plot the intensity of the reverberant sound on a logarithmic scale during the decay period, a complete decay curve being obtained each time the test tone is interrupted. When used with a beat frequency oscillator curves of intensity *vs.* frequency may be obtained. This type of curve is useful for loudspeaker and microphone calibrations for determining the distribution of sound in rooms and for intensity measurements for obtaining the sound transmission through partitions. Examples of the above types of curves and others obtained with speech and music are given.

15. Loudness of a Complex Tone, Its Definition, Measurement and Calculation. H. FLETCHER AND W. A. MUNSON, *Bell Telephone Laboratories.*

At the meeting of the Society held one year ago Fletcher presented a paper by this title in which was discussed the formulation of a promising method for computing the loudness of a non-fluctuating complex tone from the measured values of the intensity levels and frequencies of the components. Also at that time Munson presented a paper on the loudness of pure tones. The present paper combines the material of these two previous papers with the results of subsequent experimental work, describes some further modifications in the formulae of this method of computing loudness and illustrates the application of the formulae to some examples. In view of the complex nature of this problem, this computation method is not considered to be fully developed and further work is required to define its scope. In addition, it is necessary to determine experimentally to what extent the proposed computation method may be applicable to the types of fluctuating complex tones encountered in speech, music and noise.

16. Minimum Audible Sound Fields. L. J. SIVIAN AND S. D. WHITE, *Bell Telephone Laboratories.*

A paper by this title was presented at the last meeting of the society. It dealt principally with the thresholds for monaural hearing in an open sound field. Since that time the work has been extended to include the field thresholds for binaural hearing. The present paper is to report on the new data and to indicate how the threshold is modified by the observer's azimuth relative to the wave front of the sound field.

It also gives a further discussion of the relationship between the two types of threshold: the above minimum audible field (M.A.F.), and the minimum audible pressure (M.A.P.) as measured at the observer's ear-drum. It has been established that the two are different at frequencies so low that diffraction caused by the head and wave motion in the ear canal cannot be assigned as causes. Some new experimental evidence bearing on this point, is presented.

17. The Relation of the Reference Level for Loudness and Intensity Measurements of Sound to the Thermal Noise Level in Electric and Acoustic Circuits. H. FLETCHER, *Bell Telephone Laboratories.*

The reference level for comparing loudness and intensities of sound which is being considered for adoption by the American Standards Association is a sound intensity of 10^{-16} watt per square centimeter in a freely travelling wave front. It has been shown by H. Nyquist (*Thermal Agitation of Electric Charge in Conductors*, Phys. Rev. July, 1928) that the fluctuating voltage V created at the terminals of a resistance R is the same as would be caused by a power P being consumed in the resistance where

$$P=\frac{V^2}{R}=10^{-16}\frac{T}{303}\frac{\Delta f}{6000}.$$

The quantity T is the absolute temperature and Δf is the frequency band being transmitted. For an area A large compared to the wave-length the sound intensity due to thermal agitation is given by

$$JA=10^{-16}\frac{\Delta f}{6000}\frac{T}{303}.$$

For a small area compared to the wave-length Sivian and White have shown that

$$J=10^{-16}\frac{f_2^3-f_1^3}{15000^3}$$

where f_2 is the upper and f_1 the lower frequency limit of the band being transmitted. By means of the loudness formula, it is shown that the acoustic thermal noise is only a few db below the threshold

of hearing and is probably what limits very acute hearing.

18. Discussion on the Design of a Rotating Mirror Oscilloscope. R. F. MALLINA, *Bell Telephone Laboratories.*

In the laboratory and in the classroom it is sometimes useful to project the wave form of electrical or acoustical phenomena on a screen. A rotating mirror in combination with a vibrating mirror and a light source is a convenient way of showing such waves. The problem of building an instrument for such purposes is comparatively simple if a small screen is used in a dark chamber. However, if the screen is made large enough to be viewed by a dozen people or more, many difficulties arise.

The paper describes how the various parts of the apparatus may be coordinated in order to produce a comparatively bright clearly defined wave with a small incandescent lamp in a room of average illumination. The vibrator used in the apparatus may be so constructed that its response is either inversely proportional to frequency or independent of frequency. The range covered is between 100 and 3000 cycles.

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of the
Acoustical Society of America

JULY, 1933

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